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Characterization Well R-13 Completion Report



Los Alamos NM 87545

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List of Acronyms and Abbreviations

AITH	Array Induction Tool, version H
ASTM	American Society for Testing and Materials
bgs	below ground surface
BMP	best management practice
CH	cased hole
CNTG	Compensated Neutron Tool, model G
CMR	Combinable Magnetic Resonance
CVAA	cold vapor atomic absorption
DH	down hole
DR	dual rotary
DTH	down-the-hole
ECS	Elemental Capture Spectroscopy
EES	Earth and Environmental Sciences (Laboratory division)
EPA	Environmental Protection Agency
ER	Environmental Restoration (Project)
ESH	Environmental, Safety, and Health
FIP	field implementation plan
FMI	Formation Micro-Imager
FMU	facility management unit
FSF	Field Support Facility
gal.	gallon
GPIT	General Purpose Inclinometry Tool

gpm	gallons per minute
GPS	global positioning system
GR	gamma ray
HNGS	Hostile Natural Gamma Spectroscopy
hp	horsepower
IC	ion chromatography
ICPES	inductively coupled plasma emission spectroscopy
ICPMS	inductively coupled plasma mass spectrometry
ID	inner diameter
ISE	ion selective electrode
LANL	Los Alamos National Laboratory
MCFL	Micro Cylindrically Focused Log
NGS	Natural Gamma Spectroscopy
NMED	New Mexico Environment Department
NTU	nephelometric turbidity unit
OD	outer diameter
OH	open hole
psi	pounds per square inch
PVC	polyvinyl chloride
RC	reverse circulation
RRES	Risk Reduction and Environmental Stewardship Division
RLWTF	radioactive liquid waste treatment facility
SVOC	semivolatile organic compound
TA	technical area
TD	total depth
TDS	total dissolved solids
TLD	Triple detector Litho-Density
TOC	total organic compound
TPH	total petroleum hydrocarbons
UR-DTH	under-reaming down-the-hole (hammer)
VOC	volatile organic compound
WGII	Washington Group International, Inc.
WCSF	waste characterization strategy form
XRD	x-ray diffraction
XRF	x-ray fluorescence

Metric to US Customary Unit Conversions

Multiply SI (Metric) Unit	by	To Obtain US Customary Unit
kilometers (km)	0.622	miles (mi)
kilometers (km)	3281	feet (ft)
meters (m)	3.281	feet (ft)
meters (m)	39.37	inches (in.)
centimeters (cm)	0.03281	feet (ft)
centimeters (cm)	0.394	inches (in.)
millimeters (mm)	0.0394	inches (in.)
micrometers or microns (μm)	0.0000394	inches (in.)
square kilometers (km^2)	0.3861	square miles (mi^2)
hectares (ha)	2.5	acres
square meters (m^2)	10.764	square feet (ft^2)
cubic meters (m^3)	35.31	cubic feet (ft^3)
kilograms (kg)	2.2046	pounds (lb)
grams (g)	0.0353	ounces (oz)
grams per cubic centimeter (g/cm^3)	62.422	pounds per cubic foot (lb/ft^3)
milligrams per kilogram (mg/kg)	1	parts per million (ppm)
micrograms per gram ($\mu\text{g/g}$)	1	parts per million (ppm)
liters (L)	0.26	gallons (gal.)
milligrams per liter (mg/L)	1	parts per million (ppm)
degrees Celsius ($^{\circ}\text{C}$)	$9/5 + 32$	degrees Fahrenheit ($^{\circ}\text{F}$)

CHARACTERIZATION WELL R-13 COMPLETION REPORT

ABSTRACT

Characterization well R-13 was installed under implementation of the "Hydrogeologic Workplan" (LANL 1998, 59599). This well was funded and project directed by the Environmental Restoration (ER) Project as part of the implementation of the Mortandad Canyon Work Plan (LANL 1997, 56835). Execution of the drilling program was carried out by Washington Group International, Inc., under a subcontract to Los Alamos National Laboratory (LANL or the Laboratory). The well is located in Mortandad Canyon, in the east-central portion of the Laboratory. Well R-13 was designed to provide hydrogeologic and water-quality data on the regional aquifer downgradient of contaminant release sites in Mortandad and Ten Site Canyons. Specific sources of concern include the waste water treatment plant at Technical Area 50 (TA-50) and a former waste water treatment facility at TA-35 that have historically released effluent.

Hydrologic, geologic, geochemical, and geophysical information obtained during completion and subsequent sampling of regional wells will provide data for the Laboratory's hydrologic and geologic conceptual models and contribute to implementation of a Laboratory-wide groundwater-monitoring network. Monitoring of this network of wells supports the Laboratory's "Groundwater Protection Management Program Plan" (LANL 1996, 70215).

The R-13 borehole was drilled to a total depth of 1133 ft below ground surface using air-rotary drilling methods. The well was installed on February 25, 2002, to a total depth of 1029.4 ft with a single screen in the regional aquifer and equipped with a dedicated submersible pump.

The stratigraphy encountered during borehole drilling included, in descending order, alluvial sediments, the Tshirege Member of the Bandelier Tuff, the Cerro Toledo interval, the Otowi Member of the Bandelier Tuff, the Guaje Pumice Bed, upper Puye Formation sediments, Cerros del Rio Basalt, and a sedimentary sequence making up a lower section of Puye Formation. Samples of drill cuttings were collected at regular intervals for stratigraphic, petrographic, and geochemical analysis.

No perched water was encountered at R-13. The regional zone of groundwater saturation was encountered at a depth of 834 ft below ground surface in the Puye Formation. Borehole groundwater samples were collected from the regional aquifer for analysis of selected organic and inorganic constituents and radiochemical compounds. Based on the analytical results for the R-13 borehole water samples collected within the Puye Formation, it appears that contamination from Laboratory discharges is not present in the regional aquifer at this well site.

1.0 INTRODUCTION

This completion report summarizes the site preparation, drilling, well construction, well development, and related activities from August 14, 2001, to February 25, 2002, for the installation of characterization well R-13. The well is located on the floor of Mortandad Canyon approximately 5890 ft east-southeast of well R-15 and 250 ft north of the Los Alamos National Laboratory (the Laboratory) boundary that crosses Mortandad Canyon, as shown in Figure 1.0-1.

The information presented in this report was compiled from field reports and activity summaries generated by the Laboratory and subcontractor personnel. Geophysical data provided by Schlumberger, Inc. (Schlumberger) and geodetic survey results are included. Results of these activities are discussed briefly and shown in tables and figures contained in this report. Detailed analysis and interpretation of geologic, geochemical, geophysical, and hydrologic data will be included in separate technical documents to be prepared by the Laboratory.

Well R-13 was funded by the Environmental Restoration (ER) Project, now called the Risk Reduction and Environmental Stewardship (RRES) Division. Washington Group International, Inc. (WGII), under contract to the Laboratory, was responsible for executing the drilling activities.

This characterization well will function primarily to investigate the nature and extent of potential impacts to regional groundwater resulting from Laboratory activities in the Mortandad Canyon watershed. Water quality, geochemical, hydrologic, and geologic information gathered during completion will augment knowledge of regional subsurface characteristics and distribution of any contaminants downgradient of former wastewater plant at TA-35 and wastewater plant at TA-50, a potential source for groundwater contamination. Well R-13 will provide water-quality and water-level monitoring data from the regional aquifer, and data gathered from this well will be used to update the sitewide hydrologic and geologic conceptual models for the Laboratory.

Well R-13 is downstream from active and inactive outfalls at Technical Area (TA)-5, TA-35, TA-48, TA-50, TA-52, TA-55, and TA-60. From a groundwater perspective, the sources of most concern are the former wastewater treatment plant at TA-35 and the present-day wastewater treatment plant at TA-50.

The Laboratory's wastewater treatment plant at TA-35 was operated from 1951 to 1963. Routine and accidental discharges from the wastewater treatment plant resulted in release of contaminants to Ten Site Canyon (Figure 1.0-1). Contaminants of potential concern associated with the TA-35 wastewater plant include lanthanum-140; barium-140; strontium-89, -90; yttrium-90; cesium-137; ruthenium-106; plutonium-238, -239, -240; caustics; acids; sodium carbonate; strontium nitrate; iron sulfate; and dielectric oil (LANL 1997, 56835). By the early 1960s, the wastewater treatment plant at TA-35 reached its capacity to handle the increasing volume of liquid radioactive wastes associated with expanding Laboratory operations. In 1963, TA-35 wastewater operations were transferred to a new radioactive liquid waste treatment facility (RLWTF) at TA-50.

The Laboratory's RLWTF at TA-50 discharges treated wastewater to Mortandad Canyon via Effluent Canyon through an outfall that is currently permitted as NPDES outfall 051. From 1963 through 1995, a total of 342 million gal. (1,294,500 m³) of treated wastewater were discharged (LANL 1997, 56835). Laboratory surveillance data collected in Mortandad Canyon show elevated concentrations or activities of fluoride; total dissolved solids (TDS); perchlorate; nitrate; tritium; strontium-90; cesium-137; plutonium-239, -240; americium-241; and uranium-234, -235, and -238 in surface water and in alluvial groundwater.

This well completion report focuses on operational activities associated with the drilling, sampling, and completion of well R-13. Detailed analysis and interpretation of geologic, geochemical, geophysical, and

hydrologic data, included as part of previous well completion reports, will be discussed in future technical documents to be prepared by the Laboratory.

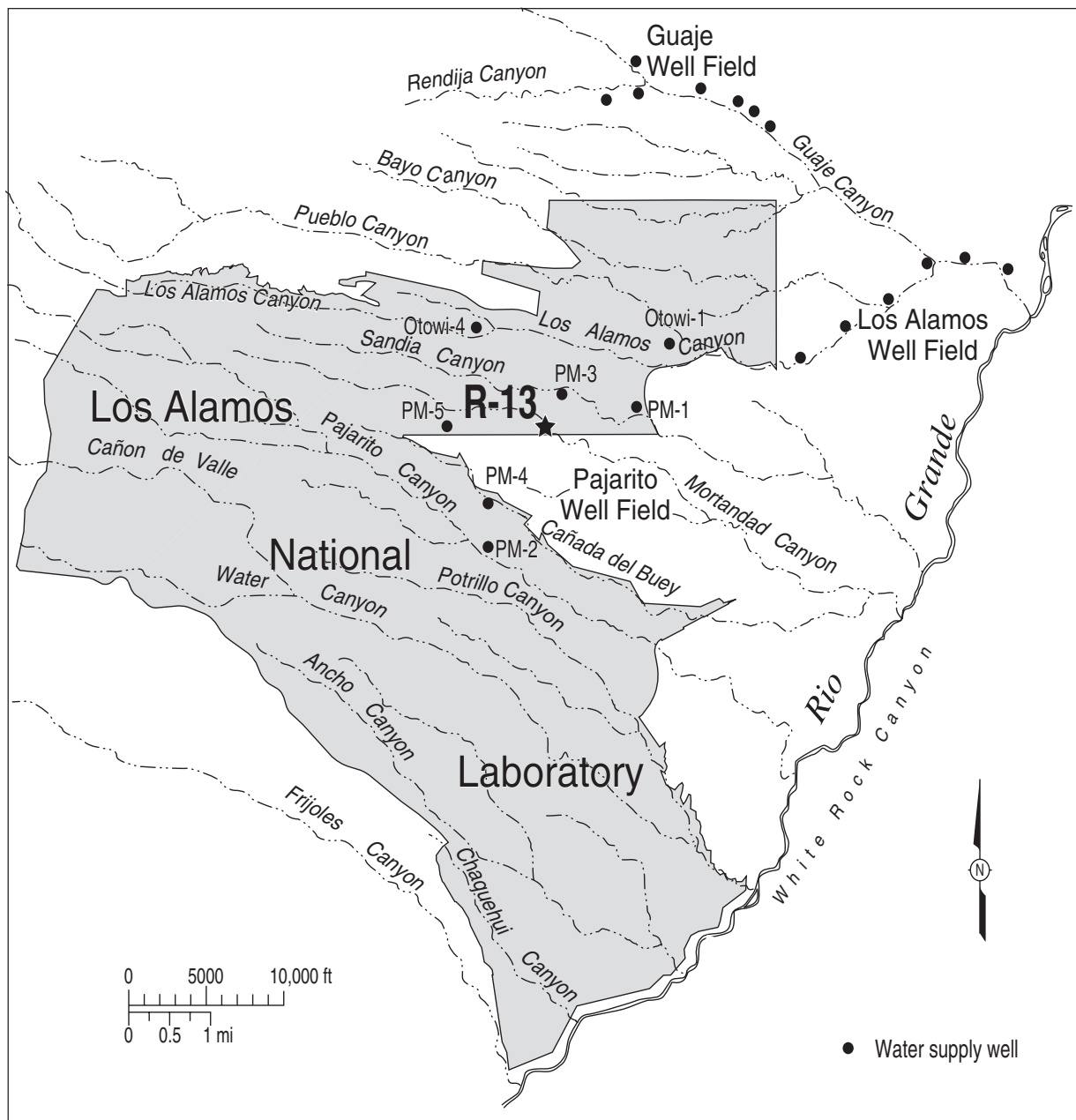


Figure 1.0-1. Map showing location of R-13

2.0 PRELIMINARY ACTIVITIES

To prepare for drilling activities, Washington Group International, Inc., (WGII) developed a modification to the existing site-specific health and safety plan, No. 273, to include well R-13. WGII also prepared the R-13 waste characterization strategy form (WCSF). The Laboratory prepared the field implementation plan (FIP) for R-13 (LANL 2001, 70291.2) which specified drilling and sampling plans to guide personnel

in executing R-13 field activities. The host facility, Facility Management Unit (FMU) 80, signed a Facility-Tenant Agreement to provide for access and security control, safety and health, and regulatory requirements for drilling and completion activities.

A Readiness Review meeting was held on August 9, 2001, to discuss administrative agreements, documents, permits, and plans pertaining to the R-13 project. A Groundwater Investigations Focus Area project representative gave authorization on August 9, 2001, to begin site preparation. The Readiness Review Checklist for drilling activities was signed on August 17, 2001.

S.G. Western Construction Company was subcontracted by WGII to conduct site preparation. Activities included site clearing, access road improvement, construction of drill pad, and construction of a lined cuttings-containment area. Site preparation was conducted from August 14 through 17, 2001 (see Figure 3.0-2).

The R-13 site was initially cleared of small trees and stumps. The drill pad was developed by leveling the area, 100 ft by 150 ft, with a grader and placing Geogrid[®] geotextile fabric over the main operations area. A primary layer of base-course gravel was then distributed and compacted over the fabric. To store R-13 drilling fluids and cuttings, a 20-ft-wide by 60-ft-long by 4-ft-deep cuttings-containment area was excavated along the north pad boundary. A berm, roughly 3 ft high, was constructed around the containment area, and the entire excavation area was lined with a 6-mil polyethylene liner. An 80-ft by 25-ft secondary containment area was graded and lined with 6-mil polyethylene to accommodate two 20,000-gallon (gal.) tank trailers used for storing drilling fluids pumped from the cuttings-containment area and development water. Drill pad construction was completed with an additional layer of base-course gravel that was also graded and compacted. Safety barriers and signs were installed around the cuttings-containment area and at the site entrance. Office and supply trailers, generators, and safety lighting equipment were moved to the site during subsequent mobilization of drilling equipment.

3.0 SUMMARY OF DRILLING ACTIVITIES

Drilling activities at R-13 were performed by Dynatec Drilling Company, Inc. (Dynatec) under contract to WGII. Dynatec provided a Foremost[™] Dual Rotary DR-24 drill rig, along with reverse circulation (RC) drilling rods and support equipment. Equipment and fabrication support for drilling activities was provided by the ER Project's Field Support Facility (FSF).

Fluid-assisted RC air-rotary methods were used to drill open hole or casing advance, as determined by changing geologic and hydrologic conditions. Municipal water mixed with polymer additives was used to improve drilling lubrication and facilitate cuttings removal from the borehole.

The objectives of drilling were to produce samples for geologic characterization, provide a borehole for well installation in the regional aquifer, and collect groundwater samples for contaminant analysis. The R-13 borehole was completed to a total depth (TD) of 1133 ft below ground surface (bgs).

Figure 3.0-1 summarizes well data and graphically depicts groundwater and geologic conditions encountered in R-13. Figure 3.0-2 summarizes graphically the chronology of drilling and other related on-site activities.

Characterization Well R-13 Completion Report

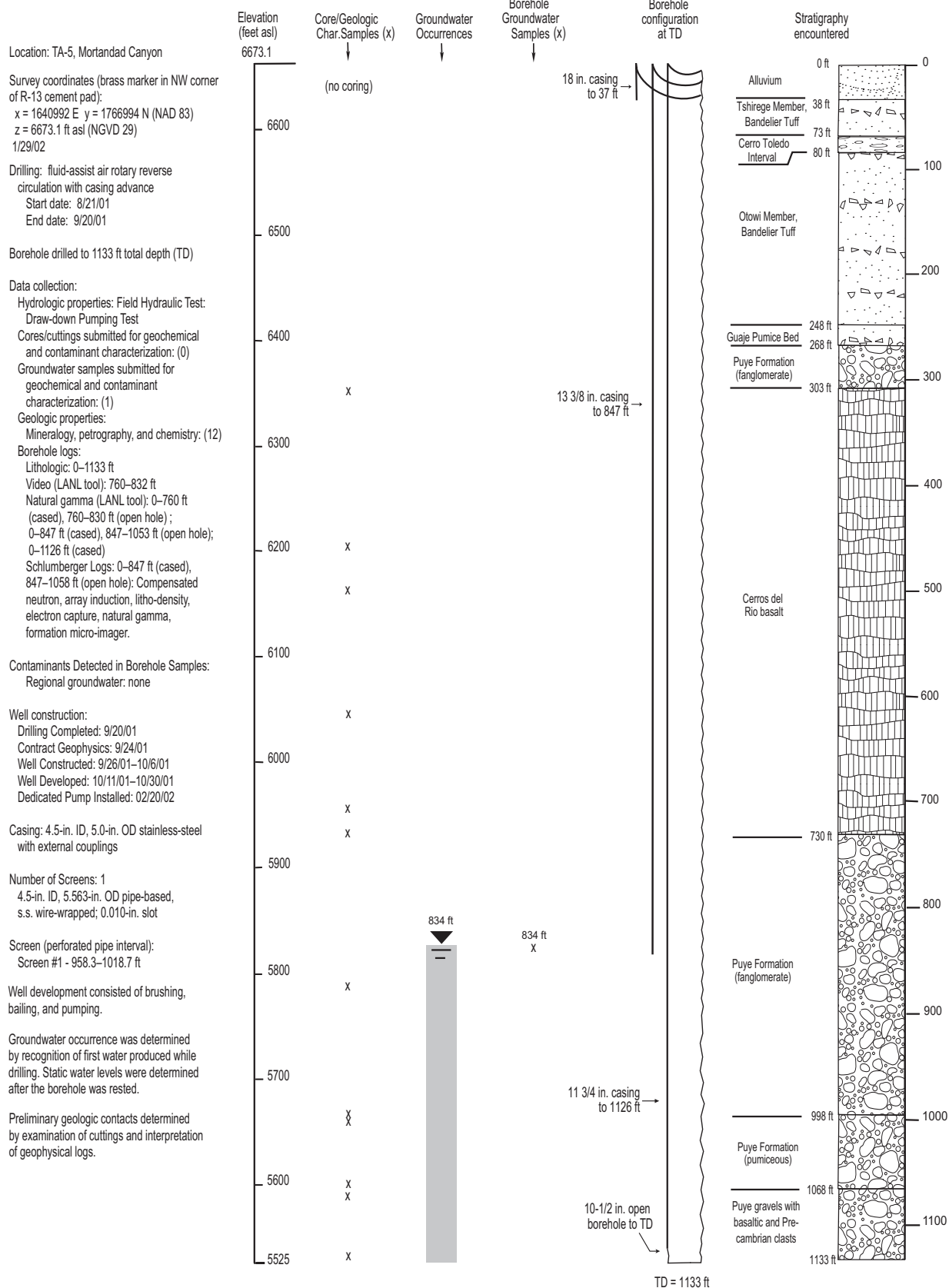


Figure 3.0-1. Well summary data sheet for R-13

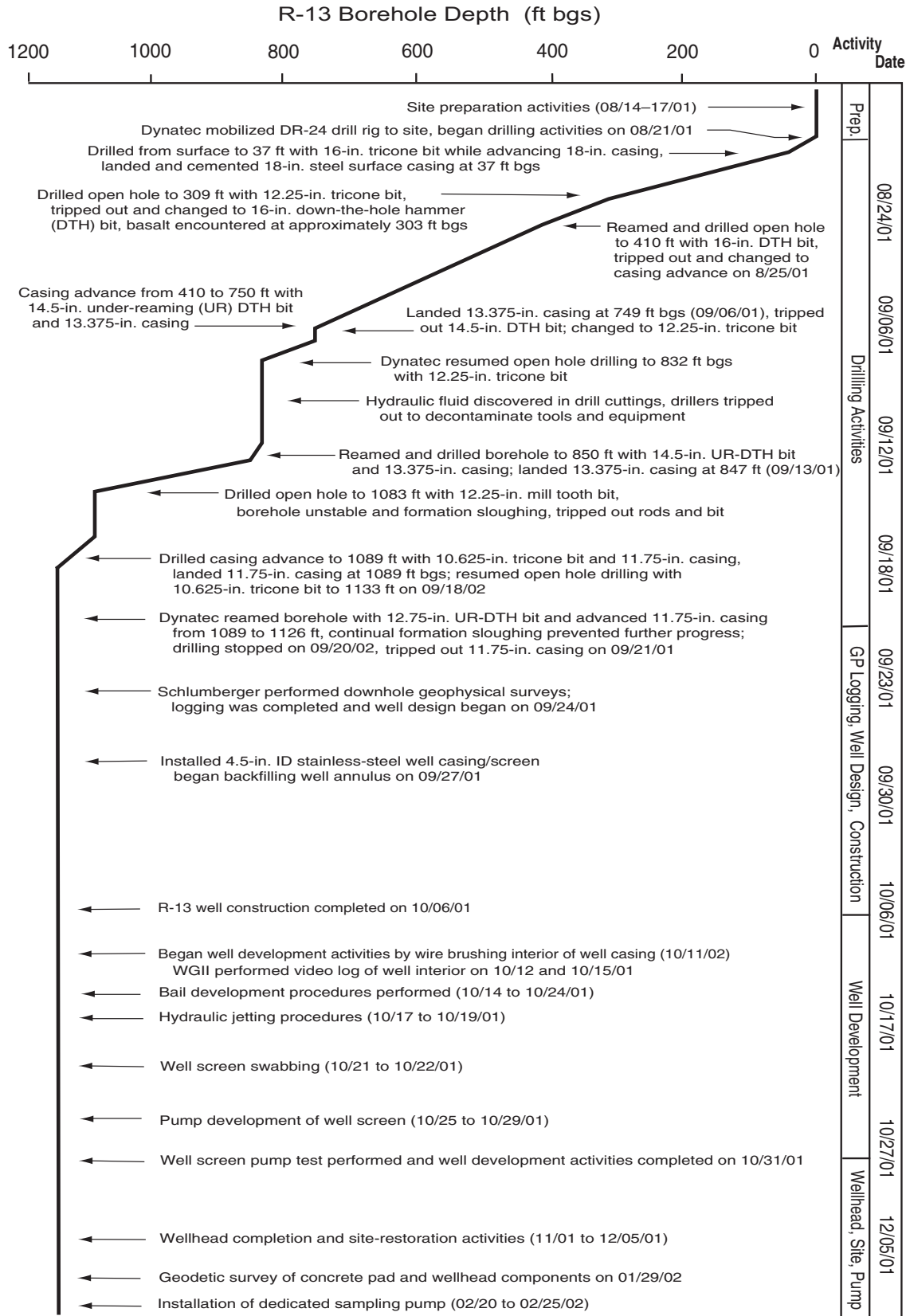


Figure 3.0-2. Operations chronology graph

Drilling activities at R-13 were conducted from August 21 through September 21, 2001 (Figure 3.0-2).

On August 21, 2001, Dynatec mobilized the DR-24 drill rig and support equipment to the site and commenced R-13 drilling operations. Dynatec initially advanced 18-in. steel conductor casing by reaming with the assistance of a 16-in. tricone long-tooth carbide button bit from ground surface to the contact between alluvium and the underlying Tshirege Member of the Bandelier Tuff. The conductor casing was landed at 37 ft bgs and cemented in place on August 22, 2001. Open hole drilling continued with a 12.25-in. tricone bit from 37 ft bgs through the Tshirege Member of the Bandelier Tuff, Cerro Toledo interval, Otowi Member of the Bandelier Tuff, including the Guaje Pumice Bed, and Puye Formation sediments. The top of the Cerros del Rio basalt was encountered at approximately 303 ft bgs.

To offset slow drilling conditions in the basalt, Dynatec switched to a 16-in. down-the-hole (DTH) bit and stabilizer. Drilling progressed to 325 ft bgs before losing circulation in the open borehole. The stabilizer was then removed from the drill string and open hole drilling continued from 325 to 410 ft.

On August 25, 2001, the annular seal outside of the 18-in. conductor casing began leaking air, and cuttings were circulating out along the outside of the casing rather than through the discharge line. To solve this problem, Dynatec advanced 13.375-in. casing using a 14.5-in. under-reaming down-the-hole-hammer (UR-DTH) bit and began casing advance drilling until a suitable depth was reached to land the casing. Drilling progressed through basalt from 410 ft to 705 ft bgs. Operations were then shut down and the site secured for the Labor Day holiday on September 3, 2001.

Drilling operations resumed on September 5, 2001. Casing advance drilling continued from 705 ft to 760 ft bgs where the 13.375-in. casing was landed in the Puye Formation, approximately 30 ft below the base of the Cerros del Rio basalt. Dynatec then changed to a 12.25-in. tricone bit and drilled open hole from 760 ft to 832 ft bgs.

Problems developed at R-13 on September 7, 2001, when hydraulic fluid was discovered in a cuttings sample collected from the 827-ft to 832-ft interval. Drilling operations were shut down until the cause and degree of contaminant impact could be ascertained. It was determined that a leak had developed in a mixing tank pump, and hydraulic fluid had been accidentally introduced into the borehole with the drill fluid. The rig's hydraulic system lost approximately 165 gal. during this incident.

At the time of the incident, the borehole had been advanced to a depth of 832 ft, and the boring was cased to a depth of 760 ft. Because of the nature of the drilling method and the configuration of the drill string, the only portion of the borehole subject to active borehole circulation was the section from the drill bit to the air exchange port. Given the configuration of the drill string at the time of the incident, an estimated 25 ft of the lowermost borehole may have been potentially impacted by hydraulic fluid.

Dynatec immediately began cleanup efforts to mitigate the effects and potential impact to the subsurface. The hose was repaired and the hydraulic oil reservoir on the rig was refilled. The hole was flushed with 500 gal. of clean water mixed with 1 cup of QUIK-FOAM®. The drill string (bit, stabilizer, and rods) was tripped out of the borehole and decontaminated with a high-pressure steam cleaner. The cyclone and cuttings trough were also decontaminated. The cleaned drill string was then tripped back into the hole, and the open hole portion of the boring was flushed with a mixture of hot water and surfactant to remediate the borehole. All fluids involved in the decontamination process were pumped into 3000-gal. polyethylene tanks for storage until they could be properly characterized for disposal. The borehole was rinsed several times to ensure that any possible aftereffects were mitigated. A water sample of the return fluids from the last rinse showed no adverse impact from the hydraulic fluid. On September 10, 2001, the borehole was purged of 300 gal. of water by circulating air through the drill stem. A sample was collected

for analysis to determine if contamination was still present in the borehole; the results showed that the borehole was free of hydraulic fluid.

Site activities were temporarily suspended on September 11, 2001, when all nonessential government operations were halted for security reasons. On September 12, 2001, the DH video camera and natural gamma-logging tool were used to assess the condition of the borehole. Logging was conducted to a depth of 830 ft. These tools showed no obvious effects from the hydraulic fluid.

As a final step to ensure that no contaminant could be carried with continued advancement of the borehole, the uncased portion of the hole was reamed to a larger diameter and the 13.375-in. casing was advanced from 760 to 850 ft. To eliminate the possibility of another occurrence of leaks, the pump mixing setup was reconfigured to avoid accidental contact of hydraulic fluid with drill water. In addition, all hydraulic lines and fittings were thoroughly inspected.

Efforts were made at the surface to contain and minimize all drill fluids and drill cuttings contaminated by the hydraulic fluid. All impacted fluids (drill and decontaminated fluids) in the cuttings pit were pumped to dedicated 3000-gal. polyethylene tanks until the waste streams could be properly characterized and arrangements made to ship and dispose of the waste. All solids (cuttings) were removed from the pit and contained in bulk rollovers until they could be characterized for shipment and disposal. In addition, all absorbent padding and 6-mil liner was also collected, contained, and readied for shipment and disposal. Table 3.0-1 shows the volumes of the different wastes generated and describes their final disposition. After the liner was removed, a soil sample was collected from the pit bottom and analyzed for total petroleum hydrocarbons (TPH) to ensure that no contamination had breached the 6-mil liner.

Table 3.0-1
R-13 Hydraulic Fluid–Contaminated Waste Streams

Waste Type/ Medium	Quantity	Final Disposition
New Mexico special/ absorbent padding and 6-mil plastic sheeting	2 yd ³	Rio Rancho Landfill, Rio Rancho, NM
Non-New Mexico special/ drill cuttings	61 yd ³	Rio Rancho Landfill, Rio Rancho, NM
Oily waste water, nonregulated/ water	5500 gal.	Rhino Landfill, Otero Co., NM

A new liner was then installed in the same location to contain the clean cuttings from the remaining borehole. The contaminated cuttings were sampled and analyzed for semivolatile organic compounds (SVOCs); benzene, toluene, ethylbenzene, and xylene; diesel range organics; TPH; and gross alpha, beta, and gamma.

The borehole was advanced open hole in Puye sediments from 850 to 963 ft bgs. During this drilling interval, groundwater was detected at a depth of 834.0 ft bgs when the drill hole depth was 964 ft. A borehole groundwater sample was collected and submitted for analysis.

On September 15, 2001, the borehole was advanced to 1083 ft bgs. Sloughing conditions rendered open-hole drilling ineffective. The 11.75-in. drill casing was advanced in an attempt to seal off flowing sands encountered in the Puye Formation. Dynatec completed tripping in of the drill casing on September 17, 2001, and continued casing advance drilling using a 10.625-in. tricone drill bit from 1030 to 1094 ft bgs. Subsequent open hole drilling advanced to a depth of 1133 ft bgs. Continued sloughing prevented further advancement of the borehole; as a result, the 10.625-in. tricone drill bit was tripped out. Casing advance

with a 12.75-in. UR-DTH bit and 11.75-in. casing resumed, in an attempt to deepen the borehole. Flowing sand and gravel conditions prohibited advancement of the borehole beyond 1133 ft bgs. The drill string and 11.75-in. casing were then tripped out in order to proceed with borehole geophysical logging operations. R-13 drilling activities were completed on September 21, 2001.

4.0 SAMPLING AND ANALYSIS OF DRILL CUTTINGS AND GROUNDWATER

During drilling operations at R-13, drill cuttings were collected according to the R-13 FIP. As drilling conditions permitted, a sufficient quantity of borehole material was collected via RC at 5-ft intervals. A portion of the cuttings was sieved (at >#10 and >#35 mesh) and placed in chip-tray bins along with an unsieved portion. These chip trays were studied to determine lithological characteristics and used to prepare the lithologic logs. The remaining cuttings were sealed in Ziploc® bags and set in core boxes for curation. No cuttings samples were submitted for contaminant analysis. Prior to curation of the chip trays and cuttings, 12 samples were removed for mineralogic, petrographic, and geochemical analyses.

During drilling operations, alluvial groundwater was thought to be encountered at 33.6 ft bgs. A sample was collected and, after analysis, it was determined to consist primarily of drilling fluid (see section 4.1). Regional groundwater was encountered at 834 ft bgs. A groundwater sample was collected from the borehole at the depth at which hydraulic fluid had been removed. The total organic carbon (TOC) was 0.70 mgC/L, suggesting that little or no residual hydraulic fluid remained in the borehole. SVOCs, including hydraulic fluid, were not detected in groundwater during the first characterization sampling round conducted at well R-13 on July 3, 2002.

4.1 Geochemistry of Sampled Waters

Waters sampled at R-13 include possible alluvial groundwater and borehole water collected from regional aquifer.

Possible alluvial groundwater was identified based on water returns at 33.6 ft, but the sample had a high solids content (>95%) and a very high viscosity. The sample was collected on August 22, 2001, and was analyzed for anions at the Laboratory's Earth and Environmental Sciences (EES) Division by the Hydrology, Geochemistry, and Geology Group (EES-6). Concentrations of anions, in parts per million, are as follows: bromide (0.07), chloride (20.1), perchlorate (<0.02), fluoride (5.09), nitrite ([as nitrogen] <0.01), nitrate ([as nitrogen] <0.01), oxalate (0.68), phosphate ([as phosphorus] 0.05), and sulfate (17.1). The source of water may include drilling water and possibly alluvial groundwater, although concentrations of perchlorate, nitrate, and nitrite were less than detection.

Two water samples were collected from the undeveloped borehole during drilling and were analyzed for a limited suite of constituents. The samples were collected at depths of 933 and 1120 ft primarily to determine if potential contaminants had been introduced from upper horizons into the regional aquifer during drilling operations. Major potential contaminants of concern at R-13 include mobile solutes such as perchlorate, nitrate, fluoride, and tritium. The two samples contain some drilling fluids (EZ-MUD® and other additives) used for lubricity and were primarily used to assist drilling decisions. The samples are not representative of purely native groundwater but provide baseline groundwater compositions that were present during drilling.

Groundwater samples analyzed for inorganic and organic chemicals and tritium were collected by circulating the water through the drill stem at depths of 933 and 1120 ft in R-13 on September 14 and 20, 2001, respectively. Temperature, turbidity, pH, and specific conductance were not determined on-site. Both filtered (metals, trace elements, and major cations and anions) and nonfiltered (tritium and TOC)

samples were collected for chemical and radiochemical analyses. Aliquots of the samples were filtered through a 0.45- μ m Gelman filter. Samples were acidified with analytical-grade nitric acid to a pH of 2.0 or less for metal and major ion analyses. All groundwater samples collected in the field were stored at 4°C until they were analyzed. Alkalinity was determined in the laboratory using standard titration techniques, which may approximate field conditions because of sample degassing, including carbon dioxide gas.

Groundwater samples were analyzed by EES-6 using techniques specified in the US Environmental Protection Agency (EPA) SW-846 manual. Ion chromatography (IC) was the analytical method used for bromide, chloride, fluoride, nitrate, nitrite, oxalate, perchlorate, phosphate, and sulfate. Ammonium was analyzed by ion selective electrode (ISE), whereas mercury was analyzed by cold vapor atomic absorption (CVAA). Inductively coupled (argon) plasma emission spectroscopy (ICPES) was used for calcium, magnesium, potassium, silica, and sodium. Aluminum, antimony, arsenic, barium, beryllium, cadmium, chromium, cobalt, copper, iron, lead, manganese, nickel, selenium, silver, thallium, vanadium, uranium, and zinc were analyzed by inductively coupled (argon) plasma mass spectrometry (ICPMS).

Tritium activity in a groundwater sample was determined by electrolytic enrichment at the University of Miami. Analyses of americium-241; cesium-137; plutonium-238, -239, -240; strontium-90; uranium-234, -235; and uranium-238 were not performed because the activity of tritium was 0.64 ± 0.29 (1 σ) pCi/L and the presence of other dissolved radionuclides is very unlikely at R-13.

The precision limits (analytical error) for major ions and trace elements were generally less than $\pm 10\%$ using ICPES and ICPMS. Samples of core were not collected from R-13 and therefore not analyzed for contaminants.

Table 4.1-1 presents the results of the screening analyses performed on the two groundwater samples collected from the Puye Formation in R-13. Based on the analytical results for the two samples, it appears that contamination from Laboratory discharges is not present in the regional aquifer at this well site.

Table 4.1-1
Hydrochemistry of Regional Aquifer Samples at R-13

Analysis	Sample from Puye Formation, 933-ft Depth, September 14, 2001	Sample from Puye Formation, 1120-ft Depth, September 20, 2001
pH (laboratory)	7.39	7.45
Alkalinity (mg CaCO ₃ /L)	61.3	66.3
Al (mg/L)	0.09	0.21
NH ₄ (as N) (mg/L)	0.03	0.55
Sb (mg/L)	0.0003	0.0005
As (mg/L)	0.0002	0.0002
B (mg/L)	0.011	0.016
Ba (mg/L)	0.023	0.032
Be (mg/L)	[0.001]U ^a	[0.001]U
Br (mg/L)	0.01	0.01
Cd (mg/L)	[0.001]U	[0.001]U
Ca (mg/L)	11.8	12.4
Cl (mg/L)	2.95	2.35

Table 4.1-1 (continued)

Analysis	Sample from Puye Formation, 933-ft Depth, September 14, 2001	Sample from Puye Formation, 1120-ft Depth, September 20, 2001
ClO ₄ (mg/L)	[0.002]U	[0.002]U
Cr (mg/L)	[0.001]U	[0.001]U
Co (mg/L)	[0.001]U	[0.001]U
Cu (mg/L)	0.0023	0.0029
F (mg/L)	0.31	0.28
Fe (mg/L)	0.06	0.15
Pb (mg/L)	[0.001]U	[0.001]U
Mg (mg/L)	3.62	4.30
Mn (mg/L)	0.11	0.14
Hg (mg/L)	0.00015	0.00013
Ni (mg/L)	0.0011	0.0026
NO ₃ (mg/L) (as N)	0.52	0.51
NO ₂ (mg/L) (as N)	0.02	0.02
C ₂ O ₄ (mg/L) (oxalate)	[0.02]U	[0.02]U
PO ₄ (mg/L) (as P)	[0.02]U	[0.02]U
K (mg/L)	2.26	2.24
Se (mg/L)	[0.001]U	[0.001]U
Ag (mg/L)	[0.001]U	[0.001]U
Na (mg/L)	12.1	11.4
SiO ₂ (mg/L)	51.4	53.1
SO ₄ (mg/L)	3.85	3.50
Tl (mg/L)	[0.001]U	[0.001]U
TOC (mgC/L) (nonfiltered)	83.4	35.5
U (mg/L)	[0.001]U	[0.001]U
V (mg/L)	[0.001]U	[0.001]U
Zn (mg/L)	0.001	0.013
δD (permil)	— ^b	−77
δ ¹⁸ O (permil)	—	−10.9
Tritium (pCi/L) (nonfiltered)	0.64 ± 0.29	—
TDS (mg/L) (calculated)	242	209

^a U = not detected.^b Dash = not analyzed.

5.0 BOREHOLE GEOPHYSICS

Using Laboratory-owned and subcontractor-owned tools, WGII and Schlumberger performed borehole geophysical logging operations at well R-13. Table 5.0-1 lists the surveys performed.

Table 5.0-1
Borehole and Well Logging Surveys Conducted in R-13

Operator	Date	Method	Cased Footage	Open-hole Interval (ft bgs)	Remarks
WGII/ The Laboratory	September 12, 2001	Video, natural gamma	0–758	758–830	To evaluate borehole conditions after down-hole discharge of hydraulic fluid, subsequent purging of hydraulic fluid, and borehole lithologies
WGII/ The Laboratory	September 15, 2001	Natural gamma	0–847	847–1053	To evaluate borehole lithologies
WGII/ The Laboratory	September 20, 2001	Natural gamma	0–1126	0	Conducted before retracting 11.75-in. drill casing and to evaluate borehole lithologies
Schlumberger	September 24, 2001	Logging suite*	0–847	847–1058	Schlumberger borehole logging conducted at TD prior to well installation
WGII/ The Laboratory	October 12, 2001	Video	0–1029	0	Filmed to 832 ft (water level) to evaluate bentonite in the well casing
WGII/ The Laboratory	January 16, 2002	Video	0–1029	0	Final as-built

* Schlumberger suite of borehole logging surveys included triple detector lithodensity, array induction tool, epithermal compensated neutron log, elemental capture sonde, full-bore formation microimager, and natural gamma ray spectrometry.

5.1 LANL-Supported Geophysical Logging

Between September 12 and January 16, 2002, natural gamma and video camera logs were performed in borehole R-13 using down-hole tools provided by the Laboratory. A series of down-hole surveys were conducted in the R-13 borehole and the installed well. The gamma logs were collected to provide lithologic and stratigraphic information that complemented data gathered from cuttings. The video logs were used to troubleshoot drilling-related problems and to observe interior conditions after well completion. Table 5.0-1 summarizes the borehole and well logs conducted in R-13.

Natural gamma logs have proven to successfully discriminate between geologic units containing varying concentrations of uranium, thorium, and potassium. The following three natural gamma logs were run.

1. The first gamma log was carried out from 0 to 830 ft bgs. At that time, the borehole contained an 18-in. surface casing from ground surface to 37 ft bgs and a 13.375-in. drill casing from ground surface to 760 ft bgs. Open borehole conditions extended from 760 to 830 ft bgs. This logging run was conducted shortly after the borehole was flushed to remove hydraulic fluid that had circulated into the bottom of the borehole.

2. The second gamma log run was inside the 13.375-in. drill casing from the surface to 760 ft bgs, with the 18-in. surface casing still in place to 37 ft bgs. The borehole was open from 760 to 1053 ft bgs.
3. The third gamma log run was inside the 11.75-in. drill casing from the surface to 1126 ft bgs, the 13.375-in. casing from the surface to 847 ft bgs, and the 18-in. casing from the surface to 37 ft bgs. In each case, measurements of natural gamma activity were obtained every 0.1 ft as the logging tool was raised upward from the bottom of the borehole at a rate of about 15 ft/min.

Video camera logs were run to assess the stability of the borehole prior to deploying the natural gamma tool and to characterize rock lithologies (bedding features, fractures, and geological contacts). One run was made to evaluate the condition of the borehole after hydraulic fluid decontamination operations. Another video log was made to view the condition of the well interior after it was discovered that a small quantity of bentonite had fallen into the well during backfilling operations. The final camera run was conducted as a quality control procedure to inspect the condition of the stainless-steel well casing and screens installed at R-13. The video log of the open borehole is presented as Appendix C, which can be found on the CD attached to the inside back cover of this report.

5.2 Schlumberger Geophysical Logging

Schlumberger personnel conducted geophysical logging in the R-13 borehole on September 24, 2001. A suite of logging surveys was performed after retracting the 11.75-in. drill casing from 1126 ft to 826 ft bgs. At that time, an 18-in. surface casing extended from ground surface to 37 ft bgs, a 13.375-in. drill casing extended from ground surface to 847 ft bgs, and an 11.75-in. drill casing extended from ground surface to 826 ft bgs. The remaining interval of the borehole between 847 and 1058 ft bgs was uncased.

The primary purpose of the Schlumberger logging was to characterize the conditions in the hydrogeologic units penetrated by the R-13 borehole, with primary emphases on gathering moisture distribution data, identifying possible perched water zones, measuring capacity for flow (porosity and moisture), and obtaining lithologic/stratigraphic data. Secondary objectives included evaluating borehole geometry and determining the degree of drilling fluid invasion along the borehole wall.

Schlumberger personnel ran a suite of geophysical logging tools in the cased borehole; the suite include the following tools:

- Array Induction Tool, version H (AITHTM), measures formation electrical resistivity and borehole fluid resistivity, thus evaluating the drilling fluid invasion into the formation, the presence of moist zones away from the borehole wall, and the presence of clay-rich zones.
- Triple detector Litho-Density (TLDTM) measures formation bulk density related to porosity, photoelectric effect related to lithology, and borehole diameter using a single-arm caliper.
- Natural Gamma Spectroscopy (NGSTM) measures spectral and overall natural gamma ray activity, including potassium, thorium, and uranium concentrations, thus evaluating geology and lithology.
- Elemental Capture Spectroscopy (ECSTM) measures concentrations of hydrogen, silicon, calcium, sulfur, iron, potassium, titanium, and gadolinium to characterize mineralogy, lithology, and water content of the formation.

- Compensated Neutron Tool, model G (CNTG™), measures volumetric water content beyond the casing to evaluate formation moisture content and porosity.
- Formation Micro-Imager (FMI™) measures electrical conductivity images of the borehole wall and the borehole diameter with a two-axis caliper to evaluate geologic bedding and fracturing, including strike and dip of these features, fracture apertures, and rock textures.

Additionally, a calibrated natural gamma tool was used to record gross natural gamma-ray activity with every logging method (except the NGS™ run) to correlate depth runs between each of the surveys conducted.

The Schlumberger interpretive logging report and the geophysical logs, compiled as a montage, can be found as Appendix D (see the CD on the inside back cover of this report).

6.0 LITHOLOGY AND HYDROGEOLOGY

A preliminary assessment of the hydrogeologic features encountered during drilling operations at R-13 is presented below. Included is a brief description of the geologic units identified during characterization of drill cuttings. Groundwater occurrences are discussed based on drilling evidence, open-hole video logging, and geophysical logging data.

6.1 Stratigraphy and Lithologic Logging

Rock units and stratigraphic relations, interpreted primarily from visual examination of drill cuttings samples and interpretation of geophysical data, are briefly discussed in order of younger to older occurrence. Such interpretations may be revised upon further analysis of petrographic, geochemical, mineralogical, and geophysical logging. A lithologic log for the R-13 borehole is provided in Appendix B.

Alluvium (0 to 38 ft bgs)

Cuttings samples indicated unconsolidated alluvium in R-13 from ground surface to approximately 38 ft bgs that represent abandoned stream channels of Mortandad Canyon. These Quaternary deposits contain tuffaceous silty sands and gravels derived from the Bandelier Tuff.

Bandelier Tuff (38 to 268 ft bgs)

The Quaternary Bandelier Tuff is comprised of the Tshirege Member, (Qbt 1g), and the Otowi Member, including the Guaje Pumice Bed. Tuffaceous sedimentary deposit of the Cerro Toledo interval separate the two members of the Bandelier Tuff.

Tshirege Member of the Bandelier Tuff, Unit 1g (38 to 73 ft bgs)

Unit Qbt 1g of the Tshirege Member of the Bandelier Tuff was encountered from 38 to 73 ft bgs. This interval represents the basal part of the Tshirege Member that is made up of nonwelded to poorly welded rhyolite ash-flow tuff. Drill cuttings indicate abundant (up to 80% by volume) vitric pumice; hence, the unit is identified as 1g (*g* representing glassy). Cuttings contain 20% or more intermediate to felsic volcanic lithic fragments and lesser amounts of quartz and sanidine crystals. The high abundance of pumice and lithic fragments indicates that much of the fine ash that is normally found in these tuffs was not collected in the cuttings sample.

The Cerro Toledo Interval (73 to 80 ft bgs)

The interval from 73 to 80 ft bgs is interpreted to represent tephra and volcanoclastic sediments of the Cerro Toledo interval. Texturally, this unit is made up of silt to very coarse sands and gravels. Pebble-size clasts are subrounded and typically composed of dacite and rhyodacite volcanics in a matrix of white vitric pumice, quartz, and sanidine crystals.

Ash-flows of the Otowi Member of the Bandelier Tuff (80 to 248 ft bgs)

R-13 penetrated 168 ft of nonwelded to poorly welded rhyolite ash-flow tuff representing the Otowi Member of the Bandelier Tuff. The upper part of this sequence contains abundant fibrous, vitric pumice fragments that are orange-tan in color. Cuttings for the Otowi Member are lithic-rich and typically contain dacitic and andesitic xenolithic fragments and 10% or less quartz and sanidine phenocrysts. The volcanic ash that comprises significant portion of this unit is poorly sampled in cuttings returns. Whole-rock chip samples frequently contain ground vitric ash that indicates the nonwelded character of the tuff matrix.

Guaje Pumice Bed (248 to 268 ft bgs)

The interval from 248 to 268 ft bgs is interpreted to represent the Guaje Pumice Bed that forms the basal unit of the Bandelier Tuff. Drill cuttings indicate that this pumiceous unit is predominantly light pinkish-gray tephra. Pumice fragments, volumetrically as much as 90%, are vitric to locally clay-altered. The remainder is made up of dacitic lithic fragments and quartz and sanidine crystals.

Upper Puye Formation (268 to 303 ft bgs)

The 37-ft-thick interval from 268 to 303 ft bgs in R-13 is made up of generally fine clastic sediments interpreted to represent an upper facies of the Pliocene Puye Formation. Cuttings in this interval are predominantly made up of indurated clay-cemented tuffaceous sandstone and siltstone with less than 10% clasts by volume of mixed volcanic lithologies, including dacite, andesite, basalt, pumice, and minor amounts of quartz and sanidine crystals.

Cerros del Rio Basalt (303 to 730 ft bgs)

R-13 intersected a series of basalt flows and scoriaceous breccias from 303 to 703 ft bgs that make up the Pliocene Cerros del Rio basalt. Basalt flows in this section are generally porphyritic with phenocrysts of olivine, pyroxene, and minor plagioclase in an aphanitic groundmass. Flows exhibit a wide range of vesicularity and are locally scoriaceous. The interval from 460 to 483 ft bgs contains abundant scoria that is reddish with iron-oxide staining, suggesting that this interval is an interflow breccia separating distinct flow events in the sequence. Evidence of local alteration in these rocks also includes alteration of groundmass minerals, iddingsite replacement of olivine phenocrysts, amygdaloidal clays, and clay or calcite coatings on fracture surfaces. Clay-coated, rounded basalt clasts in chip samples from 595 to 605 ft bgs suggest this interval may represent a sedimentary interflow deposit between basalt flows.

Lower Puye Formation (730 to 1133 ft bgs)

Stratigraphically, below the Cerros del Rio basalt R-13 encountered a sequence of clastic sediments from 730 ft bgs to the bottom of the borehole at 1133 ft bgs. This clastic sediment interval is the lower part of the Puye Formation. A wide range of deposits, from silty sands to coarse gravels, is present in this interval, and volcanoclastic materials predominate throughout the chip samples. From 730 to 998 ft bgs, the Puye Formation is dominantly composed of dacitic and basaltic clasts (up to 98% by volume) and typically contains up to 15% fine-grained tuffaceous sandstone and siltstone fragments. Trace amounts of glassy scoria, pumice, and quartz are locally present. The interval from 998 to 1068 ft bgs is notably rich

in pumice (generally 50% or more pumice) with moderate amounts of dacite, silicified dacite, rhyodacite, fine-grained volcanic sandstone, and minor basalt scoria.

The lowermost interval of the Puye Formation, from 1068 to 1133 ft bgs, exhibits a 5 to 20% by volume component of Precambrian quartzite and metamorphosed granitic rocks. Quartzite-bearing gravel horizons interlayered within Puye sediments appear to be common in the study area. Dethier (1997) referred to the Totavi Lentil as a distinct gravel subunit containing 80% or more clasts of quartzite and other Precambrian crystalline rocks. The presence of quartzite in the above-mentioned interval suggests a depositional environment that resulted in the local mixing of volcanoclastic Puye alluvial-fan sediments with axial gravels of the ancestral Rio Grande.

6.2 Groundwater Occurrence and Characteristics

Perched groundwater saturation above the regional aquifer was not predicted in the planned drilling of R-13. As anticipated, no intermediate perched water-bearing zones were encountered during operations.

Water in borehole R-13 was first observed in alluvium at 33 ft bgs. Chemical analysis of a collected sample suggested the presence of naturally occurring groundwater (see section 4.1). Water was measured and sampled again in the borehole at 672.5 ft bgs, after drilling operations were shut down for several days. Visual inspection showed that this water contained a high concentration of drilling fluids and was not naturally occurring groundwater.

Water in the regional aquifer was encountered while drilling in the lower Puye Formation at approximately 834 ft. Drilling was halted at 903 ft and again at 943 ft bgs to circulate fluids within the borehole in an attempt to observe increased water production, which did not occur. At a depth of 963 ft, drilling was again halted, and water level was measured at 832.7 ft bgs. The water level eventually stabilized at 834 ft. At the time these water-level measurements were collected, the bottom of the drill casing was at 847 ft bgs and the borehole was open to 963 ft bgs. After R-13 well installation and development activities were completed, but prior to installation of a dedicated pump, the water level had stabilized on October 28, 2001, with a measurement of 833.7 ft bgs.

7.0 WELL DESIGN AND CONSTRUCTION

Well R-13 was installed as part of the implementation of the work plan for Mortandad Canyon (LANL 1997, 56835) and the "Hydrogeologic Workplan" (LANL 1998, 59599). Sections 7.1 and 7.2 of this report describe the R-13 well design and construction, respectively.

7.1 Well Design

The Laboratory and WGII produced the well design for R-13. Information gathered from geophysical logs, borehole video logs, borehole geologic samples, water-level data, field water-quality data, and driller observations was analyzed by the Groundwater Investigations Team to plan the screen placement interval for the well. The well was designed with a single screen to monitor contaminants in the uppermost productive zone of the regional aquifer. The location of the screen below the top of regional saturation in the productive zone permits adequate development of the well. No intermediate perched zones were identified; therefore, no screens were placed above the regional aquifer. The planned and actual screen location is given in Table 7.1-1.

Table 7.1-1
Summary of Well Screen Information for R-13

Screen #	Planned Depth* (ft)	Actual Depth* (ft)	Geologic/Hydrologic Setting
1	959.1–1020.0	958.3–1018.7	Regional zone of saturation in the Puye Formation

* These intervals represent the perforated area of the screen.

7.2 Well Construction

Well R-13 casing and pipe-based screens were manufactured using 4.5-in. inner diameter (ID)/5.0-in. outer diameter (OD) type 304 stainless-steel fabricated to American Society for Testing and Materials (ASTM) A554 standards. External couplings were also type 304 stainless-steel fabricated to ASTM standard A312 and A511, both of which exceed the tensile strength of the threaded casing ends. The pipe-based screens were modified from 10-ft sections of blank well casing. The modifications made consisted of drilling 0.5-in.-diameter holes with 84 holes per ft and then welding a stainless-steel wire-wrap (with 0.010-in. spacing) over the perforated interval. The final OD of the screened sections was 5.56 in.

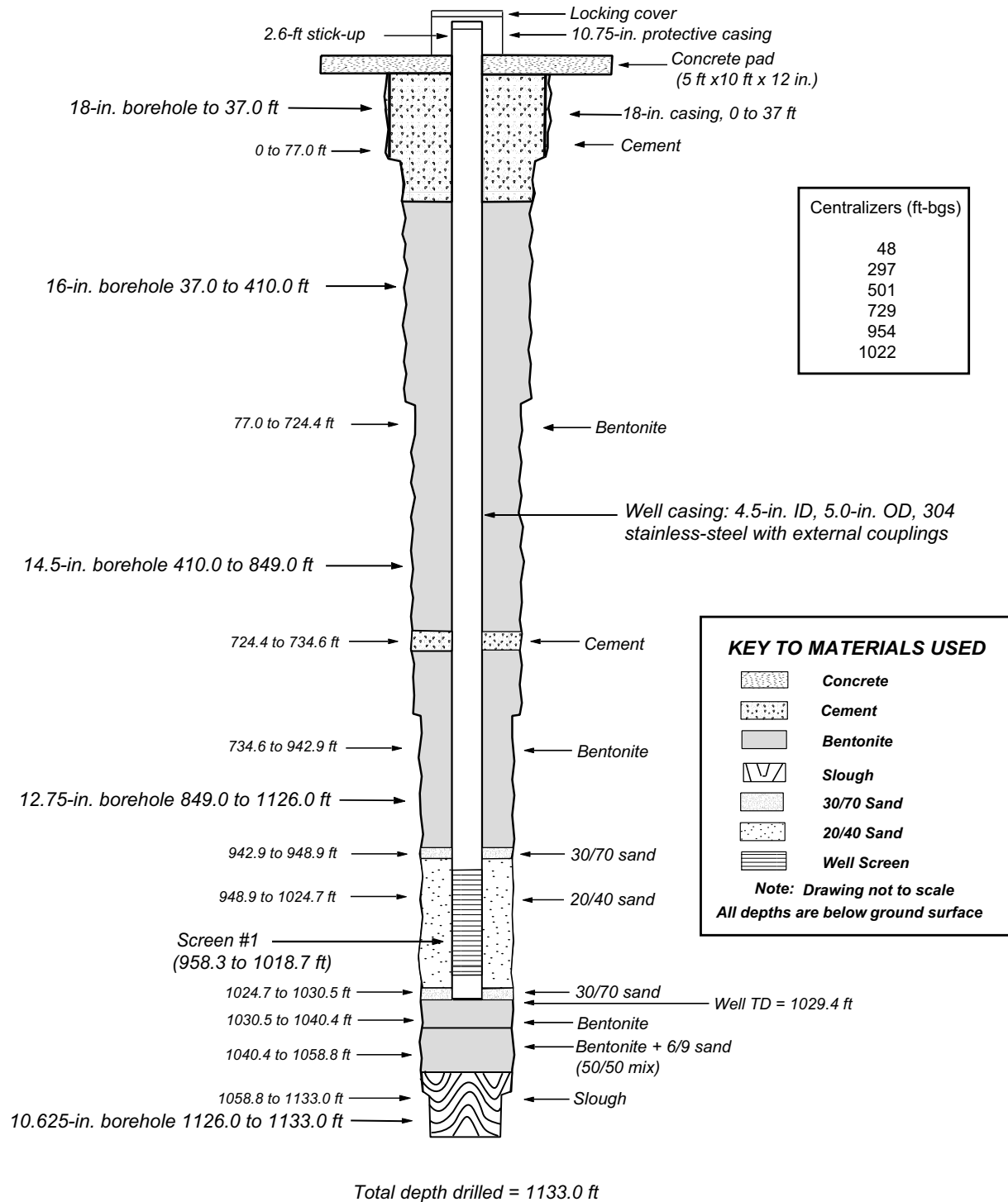
All stainless-steel well components were cleaned at the well site using a high-pressure steam cleaner and scrub brushes. All annular fill was placed in the casing/borehole annulus through a tremie pipe. Well construction activities were completed during the period from September 26 to October 6, 2001.

7.2.1 Steel Installation

Well steel installation consisted of connecting joints of stainless-steel well casing and screen sections by means of threaded couplings. The bottom of the well was set at 1029.4 ft bgs. Stainless-steel centralizers were installed above and below the screen and in several locations above the zone of regional saturation to center the well in the borehole during backfill placement operations. Dynatec installed the R-13 well casing and screen from September 26 to September 27, 2001. Figure 7.2-1 shows the as-built well casing configuration and indicates the depths of the various well components from ground surface.

7.2.2 Annular Fill Placement

Placement of annular fill consisted of using a steel tremie pipe to deliver annular fill to the specified depths (Figure 7.2-1). The bottom of the borehole was measured prior to placing the annular fill. Filter pack across the screened interval consisted of silica sand materials mixed with municipal water and placed in the annulus as a fluid slurry. Bentonite materials and sand were placed below and above the screened interval to seal the annular space and isolate the water-bearing zone. Bentonite was delivered using EZ-MUD[®] polymer mixed with municipal water as a fluid slurry. Portland cement (mixed at a ratio of 5 gal. of water to 1 bag of cement) was placed at 724.4 to 734.6 ft bgs to provide a foundation for annular fill above the regional aquifer and at 0 to 77 ft bgs to protect the annular space around the well head in the upper part of the borehole. Approximately 20,630 gal. of municipal water were used during placement of annular fill.



- Notes:
1. The screen interval lists the footage of the pipe perforations, not the top and bottom of screen joints.
 2. Pipe-based screen: 4.5-in. ID, 5.563-in. OD, 304 stainless-steel with s.s. wire wrap; 0.010-in. slot.
 3. The interval of slough at the base of the borehole consists of Puye sediments.
 4. Dedicated pump location not shown.

Figure 7.2-1. As-built configuration diagram for well R-13

Problems were encountered during placement of bentonite materials at approximately 680 ft when a bridge developed between the 13.375-in. drill casing and well casing. The contractor attempted to use the annular space between the drill and well casing to tremie the bentonite into the well. As a result, a bridge formed and a significant thickness of bentonite accumulated in the drill casing. The tremie pipe remained open below the bridge and, therefore, placement of backfill materials continued as the drill casing was removed joint by joint. With 380 ft of drill casing in the hole, the contractor pulled the entire string when the borehole was deemed stable over that interval. During removal of the last 150 ft, the well cap was dislodged and an undetermined amount of bentonite entered the well. See section 8.0, Well Development and Testing, for a description of the bentonite removal process.

Dynatec performed annular-fill activities from September 27 to October 6, 2001. Table 7.2-1 summarizes the annular fill materials installed. The final configuration of annular materials is illustrated in Figure 7.2-1.

Table 7.2-1
Annular Fill Materials Used in Characterization Well R-13

Material	Use/Function	Amount	Unit*
20/40 sand (medium-grained)	To pack screen intervals	151	bags
30/70 sand (fine-grained)	To separate filter packs from bentonite seals	23	bags
6/9 sand (coarse)	To bridge formation fractures and matrix pores	334	bags
Benseal® (bentonite)	As a high-solids, multipurpose grout	5.5	bags
Holeplug® (.375-in. angular and unrefined bentonite chips)	To provide a borehole annular seal	545	bags
Pelplug® bentonite (.25 in. by .375 in., refined elliptical pellets)	To provide a borehole annular seal below the water table	899	buckets
Portland® cement (mixed with municipal water at a ratio of 5 gal. water to 1 bag)	To provide annular support and surface seal on the upper 100 ft of the borehole	159	bags

* Sand bag = 45 lb ea, bentonite bag/bucket = 50 lb ea, cement bag = 94 lb ea.

8.0 WELL DEVELOPMENT AND HYDROLOGIC TESTING

Well development and hydrologic testing activities at R-13 were conducted from October 10 to 31, 2001. Well development procedures, described below, included wire brushing, well screen swabbing, and surging, bailing, and pumping. Development activities were followed by two single-well pumping tests.

8.1 Well Development

Well development at R-13 was performed in two stages. The initial stage consisted of wire brushing the well interior, swabbing and surging the screened interval to draw fine sediment from the constructed filter pack, and bailing to remove solid materials from the well. In the second stage, a submersible pump was lowered to the screened interval where on/off cyclic pumping was performed to remove any remaining fines from the filter pack and adjacent formation.

Criteria for well development were based on field water-quality parameters (turbidity, specific conductance, pH, and temperature). To monitor progress during each development stage, samples of groundwater were periodically collected and parameter measurements were recorded. One objective of well development was to remove suspended sediment from the water until turbidity, measured in

nephelometric turbidity units (NTU), was less than 5 NTU for three consecutive samples. Similarly, other measured parameters were required to stabilize before terminating development procedures. The well was declared sufficiently developed when the above criteria were met or could not be improved with continued pumping. Table 8.1-1 presents water quality parameter data measured at the beginning and end of each stage of well development.

**Table 8.1-1
Development of R-13**

Method	Water Removed (gal.)	Range of Parameters ^a			
		pH	Temperature (°C)	Specific Conductance (µS/cm) ^b	Turbidity (NTU)
Bailing screen	458	NA ^c	NA–19.5	298–312	317–249
Bailing/jetting	741	NA	20.0–20.5	391–182	>1000
Bailing/swabbing screen	1448	NA–8	19.9–19.1	180–170	1000–214
Pumping screen	22,063	7.48–7.8	21.3–20.3	192–139	494–2.74
Total	24,710				

^a Range is made up of value at beginning, followed by value at end, of a development method.

^b Specific conductance is reported in microsiemens per centimeter (µS/cm).

^c NA = Not measured.

Preliminary bailing from the R-13 screened interval and sump was initially performed to remove bentonite materials that had been introduced into the well during construction. An attempt to clean the interior of the well casing and screen using a wire brush was impeded when the brush became clogged with bentonite. A subsequent video camera survey showed that the casing and couplings were splattered with bentonite from the top of the well casing to 832 ft. The bentonite did not affect the screen as a minor bridge formed at the water table surface.

Bailing procedures were initiated by the drillers using a 12-gal.-capacity steel bailer to remove debris and sediment from the sump. Wire brushing was resumed, and high-pressure jetting procedures were used to dislodge the remaining bentonite from the well interior. Bailing procedures continued until all foreign matter was removed. Water turbidity was not reduced significantly and remained greater than 1000 NTU after approximately 700 gal. had been withdrawn from the well. Video logging was performed to evaluate the effectiveness of the activities in dislodging and removing the bentonite. The video logs and final water quality indicate that the jetting and bailing very effectively removed the bentonite from the well interior.

Bailing was followed by surging and swabbing techniques to enhance filter-pack development. In surging the well, a wireline-controlled surge block, with a weighted pipe attached, was used to make rapid upward strokes across the screen and to facilitate changing to a wireline bailer. Next, a swabbing tool was lowered into the well and drawn repeatedly across the screen interval while municipal water was injected at a rate of 20 gal. per min (gpm). Water turbidity exceeded 1000 NTU at the beginning and declined to 214 NTU at the end of the surging, swabbing, and bailing operation (Table 8.1-1).

Pump development procedures were applied to the screened interval (958.3 to 1018.7 ft bgs) using a 10 horsepower (hp) submersible pump. The pump intake was lowered to the bottom of the screen and the pump was cycled on at a nominal rate of 20 gpm while water samples were collected every hour for parameter measurements. The pump was then cycled off for a minimum period of 15 min to allow recovery of the water level. Next, the pump was raised approximately 2 ft and the process was repeated until the entire screen interval was traversed. Approximately 22,000 gal. of water were withdrawn from the

well at the end of 14 pumping cycles. Turbidity levels declined from 494 to 2.74 NTU during the total pump development stage (Table 8.1-1).

Figure 8.1-1 illustrates the effects of pump development on measured field parameters. The graph shows that specific conductance, pH, and temperature were stable during the latter period of pumping and that turbidity values had declined consistently to less than 5 NTU when R-13 was declared fully developed.

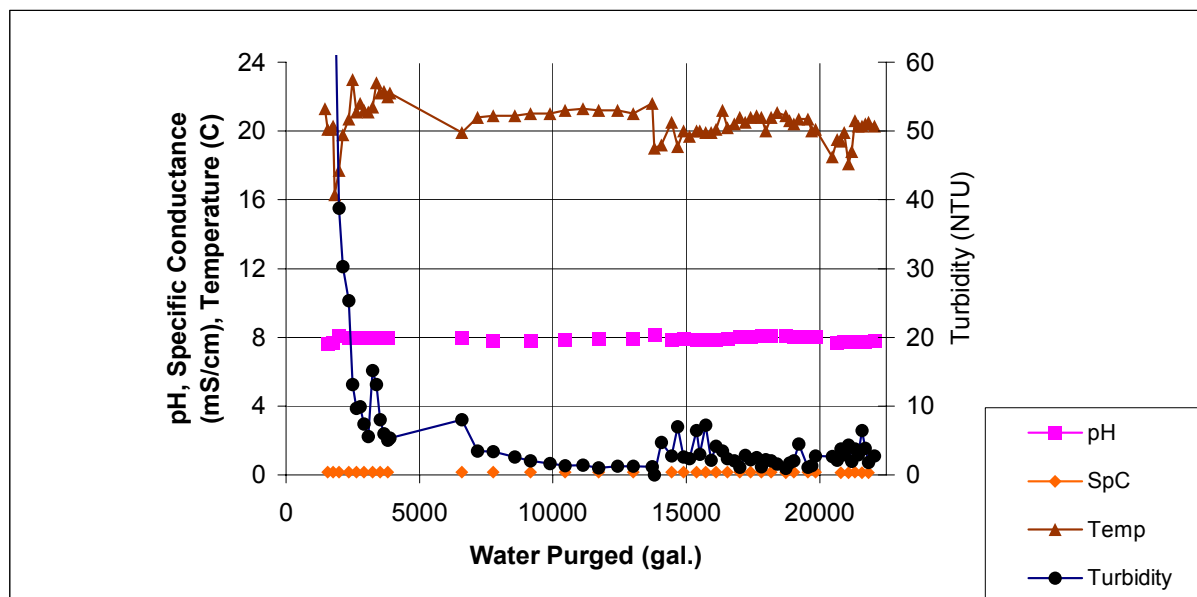


Figure 8.1-1. Effects of pump development on water-quality parameters at R-13

8.2 Hydrologic Testing

Hydrologic testing conducted in well R-13 consisted of a single-well pumping test performed on October 13, 2001, after well development was completed. The pumping test procedure involved lowering a 10 hp submersible pump intake to 931 ft, approximately 27 ft above the top of the well screen. An In-Situ, Inc., transducer (model PXD-261) was placed 10 ft above the pump intake at 921 ft bgs. The pump was turned on and run at an average continuous rate of 19 gpm for 22 min. The water level dropped 3 ft in the first minute before stabilizing for the remainder of the test. The test was repeated to verify the initial results. These tests indicate that the formation is capable of yielding up to 19 gpm. A complete discussion of hydrologic testing for well R-13 can be found in Stone and McLin (2003, 75912).

8.3 Dedicated Pump Installation

On February 20, 2002, a dedicated pump for groundwater sampling was installed in the R-13 well. The pump is a 4-in.-diameter submersible, Grundfos™ Model 10S50-48DS, with a 5 hp, 460-volt motor, rated for 11 gpm at 933 ft. The pump will be used to collect groundwater samples for water quality monitoring. The dedicated pump assembly, riser pipe, and other components were installed with a Smeal work-over rig, provided by, and operated by, Rio Grande Well Supply.

The riser pipe consisted of 1.25-in., Schedule 40S, type 304/TP 304L stainless-steel connected with 3000-lb test F304/F304L stainless-steel couplers. The thread compound used was Loctite® 567. A 1-in. Schedule 40 polyvinyl chloride (PVC) flush-thread transducer access pipe was set at the top of the pump

to permit unobstructed access for water-level measurements. The pump control leads and PVC transducer pipe were secured with stainless-steel bands to the riser pipe 5 ft above the pump and every 60 ft thereafter. In addition, the leads and PVC pipe were secured to the riser pipe every 10 ft with cold-weather vinyl cable and pipe tape that is both water and corrosion resistant. The length of the pump assembly, riser joints, and couplers were measured and assembled to ensure installation of the pump intake at 935.4 ft bgs.

The pump installation was completed and tested on February 25, 2002. The pump yielded a discharge rate of approximately 10 gpm over a 10-min period.

9.0 WELLHEAD COMPLETION AND SITE RESTORATION

After completion of the pump installation, finish work commenced on the wellhead area. Well components were surveyed, and the site underwent final clean up and restoration.

9.1 Wellhead Completion

The surface completion for well R-13 involved pouring a reinforced (5000 psi) concrete pad, 5-ft wide by 10-ft long by 12-in. thick, around the well casing to ensure long-term structural integrity of the well (Figure 9.1-1). The concrete pad was poured on December 5, 2001. A 3-in. galvanized-steel conduit was embedded vertically through the pad and connected to the protective casing to allow for future wiring of a solar power energy supply. A brass survey pin was installed in the northwest corner of the pad. A 10.75-in. steel casing with locking lid protects the well riser. Four 4-in.-diameter steel bollards were placed next to each side of the pad. The bollard next to the west side of the pad is removable to facilitate access to the well for sampling and maintenance. The pad was designed to be slightly elevated, with base course graded up around the pad to allow for drainage.

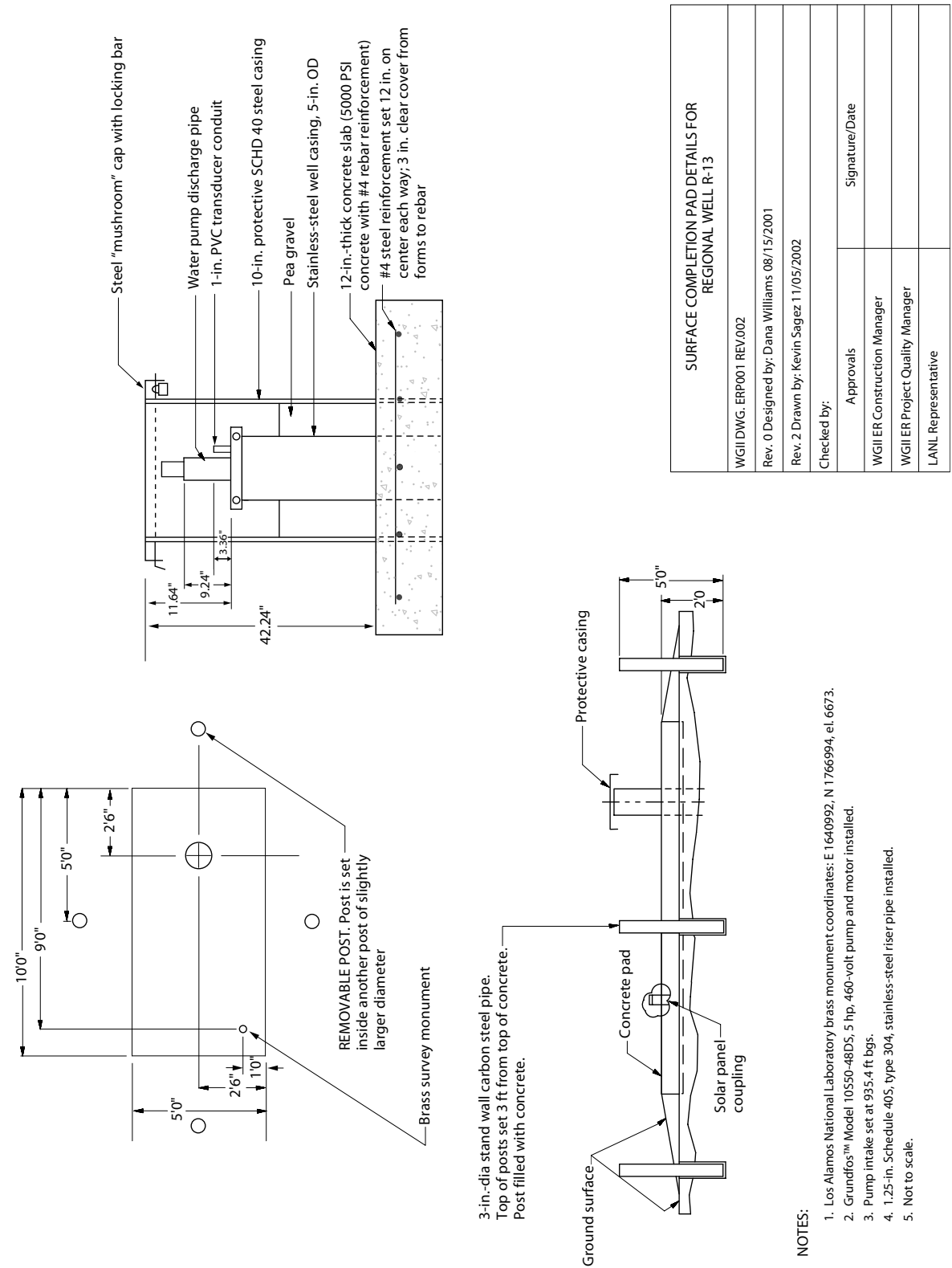


Figure 9.1-1. Surface completion configuration diagram

9.2 Geodetic Survey

The location of well R-13 was determined by geodetic survey on January 29, 2002, using a Topcon GTS 302 total station with 3-in. positional accuracy. Control points used for this survey were well MCO-13 (brass cap) and location MO-10009. Prior measurements were provided by Merrick and Co., Los Alamos National Laboratory permanent monument records. Field measurements were reduced using Plus 3 Terra Model software V-6.7. Southwest Mountain Surveys performed the survey.

This survey located the brass cap monument at well R-13 in the concrete pad as well as the four pad corners, the transducer access pipe riser, the top of the stainless-steel well casing, and the top of the 10.75-in. protective steel casing. Table 9.2-1 summarizes the results of readings conducted for various components of the completed wellhead. The coordinates shown are in New Mexico State Plane Grid Coordinates, Central Zone (North American Datum, 1983 [NAD 83]), expressed in US ft. Elevation is expressed in ft above mean sea level relative to the National Geodetic Vertical Datum of 1929.

Table 9.2-1
Geodetic Data for Well R-13

Description	East Coordinate	North Coordinate	Elevation*
Brass cap in R-13 pad	1640991.66	1766994.17	6673.05
Top of stainless-steel casing	1640988.36	1766988.39	6675.37
Transducer access pipe	1640992.71	1766993.14	6673.91
Concrete well pad corner	1640991.61	1766995.46	6672.97
Concrete well pad corner	1640995.16	1766992.07	6673.01
Concrete well pad corner	1640988.40	1766984.84	6673.01
Concrete well pad corner	1640984.85	1766988.31	6673.00
10.75-in. steel casing top	1640988.36	1766988.39	6676.23

* Measured in ft above mean sea level relative to the National Geodetic Vertical Datum of 1929.

The location identification number assigned by the Laboratory's Facility for Information Management, Analysis and Display for the R-13 well is MO-10097.

9.3 Site Restoration

From November 16, to December 5, 2001, drilling site restoration activities were conducted by S.G. Western Construction Company at R-13. Prior to and concurrent with restoration, waste management activities were also performed. Waste materials were removed from the site according to the WCSF.

Drilling activity waste streams included drilling fluids, cuttings, and development water, which were sampled for contaminant analysis. The test data were then reviewed by the New Mexico Environment Department (NMED) and the Laboratory, and the waste was approved for on-site disposal. The drill cuttings were used to help backfill the containment area, and the drilling fluids and development water were applied adjacent to the site with a 3-in. pipe irrigation system.

The waste streams included petroleum-contaminated soils and absorbent materials which had been used to clean up minor incidental spills. After the Laboratory approved the waste profile forms submitted by waste management personnel, both waste streams were disposed of as New Mexico Special Waste.

The waste associated with the hydraulic leak, including the types, volume, and final disposition, was discussed above in section 3.0.

The cuttings-containment area was excavated and the plastic lining was removed. The containment basin and water tank storage areas were then backfilled with dirt that had been bermed up during pad construction and regraded. Base-course gravel was also regraded and compacted across the site to form a smaller pad. The site was reseeded with a blend of native grasses mixed with fertilizer and mulch to facilitate regrowth of ground cover.

10.0 DEVIATIONS FROM THE R-13 FIP

Appendix A compares the actual characterization activities that were performed at R-13 with the planned activities described in the "Hydrogeologic Workplan" (LANL 1998, 59599), the "Work Plan for Mortandad Canyon" (LANL 1997, 56835), and the R-13 FIP (LANL 2001, 70291.2). Significant deviations are discussed below.

- Planned depth—the FIP stated that the approximate depth of the well would be 1700 ft bgs. The actual depth of the borehole was 1133 ft, or approximately 300 ft into the regional aquifer. Attempts were made to drill deeper than 1133 ft but, due to formation stability problems, drilling was halted.
- Number of water samples collected for contaminant analysis—intermediate perched groundwater was not encountered during drilling; two groundwater samples were obtained from the regional aquifer.
- Number of core/cuttings samples collected for contaminant analysis—the use of casing advancement techniques precluded the collection of depth-specific sidewall core samples. Additionally, the lack of intermediate perched water zones, the lack of any contaminants of concern in the screening water samples collected from the regional aquifer, and the inconclusive nature of an alluvial water zone precluded the usefulness of submission of cuttings samples.

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Dynatec Drilling Company provided the rotary drilling services.

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Southwest Mountain Surveys provided the final geodetic survey of finished well components.

D. Thompson and C. Schultz of PMC Technologies, Exton, PA; and P. Schuh, E. Tow, and R. Lawrence of Tetra-Tech EM, Inc., Albuquerque, NM; contributed to the preparation of this report.

R. Bohn and E. Louderbough, of Los Alamos National Laboratory, reviewed this report for classification and legal purposes, respectively.

D. Broxton, P. Longmire, S. Pearson, W. Stone, and D. Vaniman, of Los Alamos National Laboratory, prepared this report.

Schlumberger Integrated Water Solutions provided processing and interpretation of borehole geophysical data.

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Appendix A

*Activities Planned for R-13
Compared with Work Performed*

Activity	"Hydrogeologic Workplan" (LANL 1998, 59599)	"Work Plan for Mortandad Canyon" (LANL 1997, 56835)	R-13 Field Implementation Plan (FIP) (LANL 2001, 70291.2)	R-13 Actual Work
Planned Depth	100 to 500 ft into the regional aquifer	R-13 proposed depth of 1330 ft below ground surface (bgs)	Approximately 1700 ft bgs	Total drill depth 1133 ft bgs
Drilling Method	Methods may include, but are not limited to hollow-stem auger (HSA), air-rotary/Odex/Stratex, air-rotary/Barber rig, and mud-rotary drilling	Methods may include, but are not limited to HSA, air-rotary/Odex/Stratex, air-rotary/Barber rig, and mud-rotary drilling	Fluid-assisted, open-hole, air-rotary drilling	Same as FIP
Amount of Core	10% of the borehole	Approximately 10%	No core planned	No core collected, same as FIP
Lithologic Log	Log to be prepared from core, cutting, and drilling performance.	Log to be prepared from core, cutting, and drilling performance data.	Log to be prepared from cuttings, geophysical logs, and drilling performance.	Same as FIP
Number of Water Samples Collected for Contaminant Analysis	A water sample may be collected from each saturated zone, five zones assumed. The number of sampling events after well completion is not specified.	For planning and conceptual design purposes, it has been assumed that four water-bearing zones will be encountered. Groundwater samples will be collected from each water-bearing zone.	Up to three borehole groundwater screening samples will be collected during drilling. These samples will target groundwater in the perched zone(s) and in the regional aquifer. The number of sampling events after well completion is not specified.	One groundwater sample was obtained from the zone of the regional saturation at 903 ft bgs.
Water Sample Analysis	Initial sampling: radiochemistry I, II, and III; tritium; general inorganics; stable isotopes; volatile organic compounds (VOCs); and metals Saturated zones: radionuclides (tritium, strontium-90, cesium-137, americium-241, plutonium isotopes, uranium isotopes, gamma spectrometry, and gross alpha, gross beta, and gross gamma); stable isotopes (hydrogen, oxygen, and, in special cases, nitrogen); major ions (cations and anions); trace metals; and trace elements	Analytical suite for intermediate perched zone and regional aquifer groundwater samples: major and minor ions, trace elements, organic compounds, dissolved organic carbon, total suspended solids, total dissolved solids, neutral species (silicon dioxide), hardness, cyanide, stable and radiogenic isotopes, and radionuclides.	Metals (dissolved); anions (dissolved); gamma spectrometry; ^{241}Am ; ^{137}Cs ; ^{238}Pu ; $^{239,240}\text{Pu}$; ^{234}U ; ^{235}U ; ^{238}U ; ^{90}Sr (total); stable isotopes $^{18}\text{O}/^{16}\text{O}$, D/H, $^{15}\text{N}/^{14}\text{N}$; tritium; tritium (low level or direct counting); mobile radiological screening for gross alpha, gross beta, gross gamma; total uranium by inductively coupled plasma mass spectroscopy (ICP-MS); total Kjeldahl nitrogen; ClO_4^- .	Same as FIP
Water Sample Field Measurements	Alkalinity, pH, specific conductance, temperature, turbidity	Alkalinity, pH, specific conductance, temperature, dissolved oxygen, turbidity	pH, specific conductance, temperature, turbidity	Same as FIP

Activity	“Hydrogeologic Workplan” (LANL 1998, 59599)	“Work Plan for Mortandad Canyon” (LANL 1997, 56835)	R-13 Field Implementation Plan (FIP) (LANL 2001, 70291.2)	R-13 Actual Work
Number of Core/Cuttings Samples Collected for Contaminant Analysis	Twenty samples of core or cuttings to be analyzed for potential contaminant identification in each borehole.	Sample locations are based on predicted formation depths.	Up to five core/cuttings samples will be collected for geochemical and contaminant characterization within water-bearing zones encountered during drilling.	No core or sidewall core samples were collected. No cuttings samples were submitted for contaminant analysis.
Core/Cuttings Sample Analytes	Uppermost sample to be analyzed for a full range of compounds: deeper samples will be analyzed for the presence of radiochemistry I, II, and III analytes, tritium (low- and high-detection levels), and metals. Four samples to be analyzed for VOCs.	Analytical suite for borehole core samples includes anions, trace elements, organic compounds, total organic carbon, cyanide, and radionuclides.	Testing of core/cutting samples may include radionuclides, metals, and anions, at the discretion of the geochemistry lead.	Cuttings samples were submitted for contaminant analysis.
Laboratory Hydraulic Property Tests	Physical properties analyses will be conducted on five core samples and will typically include moisture content, porosity, particle density, bulk density, saturated hydraulic conductivity, and water retention characteristics.	Physical properties analyses will be conducted on core samples and will typically include moisture content, moisture potential, and saturated hydraulic conductivity.	Not specified in plan	No samples submitted
Geology	Ten samples of core or cuttings will be collected for petrographic, x-ray fluorescence (XRF) and x-ray diffraction (XRD) analyses.	Selected samples of core or cuttings will be collected for petrographic, XRF, XRD, and K/Ar or $^{39}\text{Ar}/^{40}\text{Ar}$ isotopic dating analyses.	The geology task leader will determine the number of samples for characterization of mineralogy, petrography, and rock chemistry based on geologic and hydrologic conditions encountered during drilling.	Twelve samples were characterized for mineralogy, petrography, and rock chemistry.

Activity	"Hydrogeologic Workplan" (LANL 1998, 59599)	"Work Plan for Mortandad Canyon" (LANL 1997, 56835)	R-13 Field Implementation Plan (FIP) (LANL 2001, 70291.2)	R-13 Actual Work
Geophysics	<p>In general, open-hole geophysics includes caliper, electromagnetic induction, natural gamma, magnetic susceptibility, borehole color videotape (axial and sidescan), fluid temperature (saturated), single-point resistivity (saturated), and spontaneous potential (saturated).</p> <p>In general, cased-hole geophysics includes gamma-gamma density, natural gamma, and thermal neutron.</p>	<p>Geophysical logs will be run in the boreholes, and compact neutron moisture logs may be run in shallower portions of the boreholes. Natural gamma, neutron moisture, and density logs may be run in shallower portions of the boreholes. Natural gamma, neutron moisture, and density logs may be run if the drilling method and borehole stability permit. Other geophysical logs may be considered if, in the opinion of the technical team, they will satisfy a technical need. In general, open-hole geophysics includes caliper, electromagnetic induction, magnetic susceptibility, borehole color videotape (axial and sidescan), fluid temperature (saturated), single-point resistivity (saturated), and spontaneous potential (saturated).</p> <p>In general, cased-hole geophysics includes gamma-gamma density, natural gamma, and thermal neutron.</p>	<p>Typical wireline logging service as planned: open-hole geophysics includes array induction imager, triple lithodensity, combinable magnetic resonance, natural gamma, natural gamma spectrometry, epithermal compensated neutron log, caliper, full-bore formation microimager, elemental capture spectrometer, and borehole videotape.</p> <p>In general, cased-hole geophysics includes triple lithodensity, natural gamma, natural gamma spectrometry, epithermal compensated neutron log and elemental capture spectrometer.</p>	<p>Video (LANL tool): 760–832 ft and 847–1053 ft bgs</p> <p>Natural gamma (LANL tool): 0–830 ft bgs (cased 0–758 ft bgs), 0–1053 ft bgs (cased 0–847 ft bgs) and 0–1126 ft bgs (cased 0–1126 ft bgs)</p> <p>Schlumberger geophysics 0–1058 ft bgs (cased 0–847 ft bgs): compensated neutron, array induction, litho-density, electron capture, natural gamma, formation micro-imager</p>
Water-Level Measurements	Procedures and methods not specified in "Hydrogeologic Workplan"	Procedures and methods not specified in "Hydrogeologic Workplan"	Water levels will be determined for each saturated zone by water-level meter or by pressure transducer.	Water-level meter used to measure the regional water table
Field Hydraulic Property Tests	Not specified in "Hydrogeologic Workplan"	Not specified in "Hydrogeologic Workplan"	Slug or pumping tests may be conducted in saturated intervals once the well is completed.	Two single-well pumping tests performed.
Surface Casing	Approximately 20-in. outer diameter (OD) extends from land surface to 10-ft depth in underlying competent layer and grouted in place	Approximately 20-in. OD extends from land surface to 10-ft depth in underlying competent layer and grouted in place.	18-in. OD schedule 40, low carbon steel casing will be installed as deep as possible below ground level (nominally 35–40 ft bgs) and will extend approximately 3 ft above the ground surface and cemented in place.	18-in. OD steel casing set at 37 ft bgs and cemented in place

Activity	"Hydrogeologic Workplan" (LANL 1998, 59599)	"Work Plan for Mortandad Canyon" (LANL 1997, 56835)	R-13 Field Implementation Plan (FIP) (LANL 2001, 70291.2)	R-13 Actual Work
Minimum Well Casing Size	6.625-in. OD	6.625-in. OD	5-in. OD × 4.5-in. inner diameter (ID)	5-in. OD (4.5-in. ID) stainless-steel casing w/ external couplings
Well Screen	Machine-slotted (0.01-in.), stainless-steel screens with flush-jointed threads; number and length of screens to be determined on a site-specific basis and proposed to the New Mexico Environment Department (NMED).	Machine-slotted (0.01-in.), stainless-steel screens with flush-jointed threads; number and length of screens to be determined on a site-specific basis and proposed to NMED.	Well screen shall be constructed with multiple sections of 5.56-in. OD, pipe-based stainless-steel screen with a 0.01 in. slot size.	Same as FIP
Filter Material	>90% silica sand, properly sized for the 0.010-in. slot size of the well screen; extends 2 ft above and below the well screen	>90% silica sand, properly sized for the 0.010-in. slot size of the well screen; extends 2 ft above and below the well screen	Primary filter pack shall consist of round, clean, washed and resieved silica sand with a uniformity coefficient of 2.0 or less, placed 10 ft above and 5 ft below the well screen. The size of the filter pack shall be selected based on the characteristics of the formation to be screened. Secondary filter pack is finer silica sand placed 2 ft above and below the primary pack.	Primary filter pack constructed of 20/40 silica sand placed 6 ft below and 10 ft above the screen. Secondary filter pack constructed of 30/70 silica sand placed in a 6-ft-thick layer above and below the primary filter pack.
Annular Fill Material (exclusive of filter materials)	Uncontaminated drill cuttings below sump and bentonite above sump	Uncontaminated drill cuttings below sump and bentonite above sump	Bentonite, gravel, silica sand, and/or cement in borehole below well; fine sand in transition zone; 50% bentonite and 50% gravel or sand above transition zone to bottom of surface casing; cement grout between surface casing and borehole wall and between surface casing and well casing.	Sand and bentonite in borehole below well casing; bentonite seal below filter pack; bentonite above filter pack. One cement grout plug 724.4 to 734.6 ft bgs and cement from surface to 77 ft bgs.
Sump	Stainless-steel casing with an end cap	Stainless-steel casing with an end cap	5-in.-diameter stainless-steel casing, 30 ft long	5-in.-diameter stainless-steel casing, 10 ft long
Bottom Seal	Bentonite	Bentonite	Bentonite	Same as FIP

Appendix B

Lithology Log

Geologic Unit	Lithologic Description	Sample Interval (ft bgs)	Elevation Range (ft above msl)
Qal, alluvium	No sample collected.	0–23	6673.1–6650.1
	Unconsolidated sediments, silt (SM), grayish-orange (10YR 7/4), composed of nonwelded vitric pumice. +35F (i.e., plus No. 35 sieve sample fraction): 20% quartz and sanidine crystals, 80% ash. +60F (i.e., plus No. 60 sieve sample fraction): predominantly ash.	23–28	6650.1–6645.1
	Unconsolidated sediments, silty gavel with sand (GM), grayish-orange (10YR 7/4), composed of nonwelded vitric tuff, lithic poor. +35F: predominantly quartz and sanidine crystals.	28–33	6645.1–6640.1
	No sample recovery.	33–38	6640.1–6635.1
Qbt 1g, Tshirege Member of the Bandelier Tuff	Rhyolite tuff, pale brown (5YR 5/2), pumice-rich, nonwelded. +10F: (i.e., plus No. 10 sieve sample fraction) 60–70% subrounded vitric pumice fragments; 15–20% intermediate to felsic volcanic lithics; 10% quartz and sanidine phenocrysts; 5% clasts that are weakly cemented with clay and iron-oxide.	38–43	6635.1–6630.1
	Rhyolite tuff, light brown (5YR 5/2), pumice-rich, nonwelded. +10F: 80% vitric pumice clasts, subrounded; 20% intermediate to felsic volcanic clasts, minor quartz and sanidine crystals (locally, clasts and crystals are weakly cemented with clay). +35F: dominantly quartz and sanidine crystals with lesser amounts of pumice and volcanic lithics.	43–53	6630.1–6620.1
	Rhyolite tuff, pale yellowish-brown (5YR 6/2), pumice- and lithic-rich, poorly welded. +10F: 50% vitric pumice clasts; 50% intermediate to felsic volcanic clasts, subrounded. +35F: composed of pumice, quartz and sanidine crystals, and minor lithics.	53–58	6620.1–6615.1
	Rhyolite tuff, grayish-orange (10YR 7/4), pumice-rich, nonwelded. +10F: 50% glassy pumice fragments, subrounded; 50% intermediate to felsic volcanic clasts. +35F: 60% pumice, 30% volcanic lithics, 10% quartz and sanidine crystals.	58–63	6615.1–6610.1
	Rhyolite tuff, very light gray (N8), lithic-rich, nonwelded. +10F: 70–100% dacite fragments (up to 5 mm), subangular; 10–30% quartz and sanidine crystals; minor pumice. Volcanic clasts commonly silicified, with clay rims.	63–73	6610.1–6600.1
Qct, Cerro Toledo Interval	Tephra deposit /tuffaceous sediments, silty sand with gravel (SM), light pinkish-gray (5YR 8/1), silt to very coarse sand and pebbles. +10F: 60–70% gray to light brown hornblende dacite and rhyodacite lithics, clasts (up to 1.0 cm) are broken to subrounded; 30–40% white vitric pumice. +35F: 70–80% pumice, 5–10% quartz and sanidine crystals, 15–25% dacite lithics.	73–78	6600.1–6595.1
	Tephra deposit/tuffaceous sediments, sand with gravel (SW), pale orange-gray (10YR 8/2), silt to very coarse sand, gravel clasts (up to 8 mm) angular to subrounded +10F: 60–70% gray to pinkish dacite, 30–40% brown to orange-tan vitric pumice. +35F: 10% pumice, 30% volcanic lithics, 60% quartz and sanidine crystals. Note: sudden increase in free crystals and appearance of oxidized pumice fragments suggest the stratigraphic top of Qbo, estimated at 80 ft bgs.	73–83	6595.1–6585.1

Geologic Unit	Lithologic Description	Sample Interval (ft bgs)	Elevation Range (ft above msl)
Qbo, Otowi Member of the Bandelier Tuff	Rhyolite tuff, light pinkish-gray (5YR 8/1), nonwelded. +10F: 30–40% pinkish-gray and reddish dacite; 60–70% fibrous porphyritic vitric pumice, pale orange, vitric luster (up to 1.8 cm). +35F: 20–30% pumice, 30–40% lithic, 30–40% quartz and sanidine crystals.	83–88	6585.1–6580.1
	Rhyolite tuff, pinkish-gray (5YR 8/1), poorly to nonwelded. +10F: 60–70% dacite and andesite lithic fragments, 10–30% white to light orange-tan pumice (up to 1.0 cm).	88–103	6580.1–6565.1
	Rhyolite tuff, pinkish-gray (5YR 8/1), nonwelded. +10F: 80–90% pumice fragments, large (up to 1.5 cm), fibrous texture; 10–20% dacite lithics.	103–113	6565.1–6555.1
	Rhyolite tuff, pinkish-gray (5YR 8/1), poorly to nonwelded. +10F: 50–60% dacite and latite lithic fragments, 40–50% white and tan pumice (up to 1.0 cm) pumice. +35F: 10–20% pumice, 20–30% lithics, 30–40% quartz and sanidine crystals. WR (i.e., unsieved whole rock) sample has ashy matrix.	113–128	6555.1–6540.1
	Rhyolite tuff, pinkish-gray (5YR 8/1), lithic-rich, nonwelded. +10F: 90–95% dacite lithic fragments (0.5 to 1.5 cm), 5–10% quartz and sanidine crystals, 5–10% pumice. +35F: 3–5% pumice; 20–30% volcanic lithics; 65–75% pumice.	128–143	6540.1–6525.1
	Rhyolite tuff, grayish-orange pink (5YR 7/2), lithic-rich, nonwelded. +10F: 60–70% dacite lithic (up to 2.0 cm), 30–40% vitric pumice fragments, 5–10% quartz and sanidine crystals. +35F: 15–25% pumice, 30–40% volcanic lithics, 30–40% quartz and sanidine crystals. WR sample has ashy matrix.	143–148	6525.1–6520.1
	Rhyolite tuff, pale yellowish-brown (10YR 6/2), nonwelded. +10F: 70–80% dacite and latite fragments (up to 2.0 cm); 15–25% fibrous textured pumice, 5–10% quartz and sanidine crystals. +35F: 5–10% pumice, 30–40% lithics, 40–50% quartz and sanidine crystals.	148–153	6520.1–6515.1
	Rhyolite tuff, pale yellowish-brown (10YR 6/2), nonwelded. +10F: 65–75% dacite and latite fragments, 10–20% fibrous pumice (up to 2.0 cm), 5–10% quartz and sanidine crystals, 10–20% fragments of indurated tuff; spotty Mn-oxide coatings on some pumices. +35F: 10–30% pumice, 20–40% lithics, 50–70% quartz and sanidine crystals. WR sample contains abundant ash.	153–168	6515.1–6500.1
	Rhyolite tuff, very pale orange (10YR 8/2), nonwelded. +10F: 80–90% dacite and latite fragments (up to 1.0 cm), 5–10% quartz and sanidine crystals, 5–10 pumice. +35F: 35–45% white and brown pumice, 20–30% lithics, 30–40% quartz and sanidine crystals. WR sample has ashy matrix.	168–183	6500.1–6485.1
	Rhyolite tuff, grayish-orange pink (5YR 7/2), ash-rich, nonwelded. +10F: 60–70% dacite fragments, 5–10% quartz and sanidine crystals, 15–25% pale tan vitric pumice (up to 1.0 cm), pumices commonly exhibit spotty Mn-oxide coatings. +35F: 20–30% pumice, 30–40% lithics, 30–40% quartz and sanidine crystals. WR sample has ashy matrix.	183–188	6485.1–6480.1

Geologic Unit	Lithologic Description	Sample Interval (ft bgs)	Elevation Range (ft above msl)
Qbo	Rhyolite tuff, grayish-orange pink (5YR 7/2), nonwelded. +10F: 60–70% dacite and latite fragments, 20–30% vitric pumice fragments (up to 3 mm) with local Mn-oxide coatings; 10% coarse quartz and sanidine crystals (up to 3 mm). +35F: 30–40% pumice, 20–30% lithics, 40–50% quartz and sanidine crystals. WR sample has ashy matrix.	188–193	6480.1–6475.1
	Rhyolite tuff, pinkish-gray (5YR 8/1), pumice- and lithic-rich, nonwelded. +10F: 65–75% dacite and andesite fragments (up to 2.0 cm), 10–15% pumice, 5–10% quartz and sanidine crystals. +35F: 10–15% pumice, 20–30% lithics, 60–70% quartz and sanidine crystals. WR sample has ashy matrix.	193–203	6475.1–6470.1
	Rhyolite tuff, light pinkish-gray (5YR 8/1), lithic-rich, nonwelded. +10F: 70–80% dacite and andesite fragments (up to 2.0 cm) commonly coated with clay, 10–15% vitric pumice (up to 1.8 cm), 5–10% quartz and sanidine crystals. +35F: 10–30% pumice, 20–30% lithics, 50–70% quartz and sanidine crystals. WR sample has ashy matrix.	203–213	6470.1–6460.1
	Rhyolite tuff, pinkish-gray (5YR 8/1), nonwelded. +10F: 60–70% dacite and latite fragments, 25–30% white vitric pumice fragments (coarse, up to 2.3 cm) with local Mn-oxide coatings, 5–10% quartz and sanidine crystals. +35F: 15–25% pumice, 15–20% lithics, 60–70% quartz and sanidine crystals. WR sample has ashy matrix.	213–223	6460.1–6450.1
	Rhyolite tuff, light gray (N7), nonwelded. +10F: 65–75% reddish-brown to gray dacite and latite fragments, 20–30% white to pale tan pumice fragments (up to 1.0 cm) with local Mn-oxide coatings, 3–5% quartz and sanidine crystals. +35F: 40–50% pumice, 25–30% lithics, 15–20% quartz and sanidine crystals. WR sample has ashy matrix.	223–233	6450.1–6440.1
	Rhyolite tuff, very light gray (N8), pumice-rich, nonwelded. +10F: 15–20% dacite and latite fragments, 60–70% vitric pumice fragments (up to 1.5 cm), 3–5% quartz and sanidine crystals.	233–238	6440.1–6435.1
	Rhyolite tuff, very light (N8), pumice-rich, nonwelded +10F: 20–25% reddish to dark gray dacite lithic fragments (up to 1.2 cm), 70–75% vitric pumice (up to 1.5 cm), 5–10% quartz and sanidine crystals. +35F: 20–30% pumice, 20–30% lithics, 40–60% quartz and sanidine crystals.	238–248	6435.1–6425.1
Qbog, Guaje Pumice Bed	Tephra deposit/tuffaceous sediments, light pinkish-gray (5YR 6/1), vitric, pumice-rich, nonwelded. +10F: 80–90% pumice fragments (0.5 to 2.0 cm), 2–10% dacite lithics, 5–10% quartz and sanidine crystals. Note: 50% of pumices altered to brown clay in 263 to 268 ft interval. The presence of clay-cemented tuffaceous sandstone indicates the basal portion of the Qbog and the proximity to the Puye Formation contact at 268 ft.	248–268	6425.1–6405.1
Tpf, Puye Formation	Clastic sediments, silty sand (SM) with gravel, light brown (5YR 6/4), pebbles (up to 1.0 cm) are subangular to subrounded. WR/+10F: composed of indurated clay-cemented tuffaceous sandstone, various volcanic (andesite, rhyodacite, basalt) rocks, lesser quartz and sanidine crystals (frosted crystal faces), minor pumice.	268–283	6405.1–6390.1
Tpf	Clastic sediments, clayey sand (SC) with gravel, light pinkish-tan (5YR 7/2), pebbles (up to 1.0 cm) are subangular to subrounded. WR/+10F: 85–95% indurated tuffaceous sandstone and siltstone, 5–15% various volcanic (andesite, basalt, pumice) rocks that are locally clay coated.	283–303	6390.1–6370.1

Geologic Unit	Lithologic Description	Sample Interval (ft bgs)	Elevation Range (ft above msl)
Tb, Cerros del Rio Basalt	Light brown (5YR 7/2), weathered basalt fragments. WR/+10F: 90% broken basalt fragments (up to 0.5 cm), 10% clay. Basalt Tpf contact with underlying basalt estimated at 303 ft.	303–308	6370.1–6365.1
	Basalt, medium gray (N5), weakly porphyritic with aphanitic groundmass, highly vesicular to scoriaceous. WR/+10F: 95–98% olivine basalt; 2–5% other volcanic rocks (andesite, pumice), quartz and sanidine crystals, and tuffaceous sandstone. Clasts are angular to subangular.	308–325	6365.1–6348.1
	Basalt, medium gray (N4), porphyritic with aphanitic groundmass, vesicular. WR/+10F: pale green olivine phenocrysts (10% of volume), euhedral crystals (1–2 mm) locally replaced by iddingsite; fracture and vesicle surfaces coated by white clay.	325–340	6348.1–6328.1
	Basalt, medium gray (N5), porphyritic with aphanitic groundmass, vesicular. WR/+10F: pale green olivine phenocrysts, commonly euhedral (up to 5 mm), less abundant euhedral plagioclase; minor clay lining vesicles.	340–360	6328.1–6308.1
	Basalt, medium gray (N5), slightly porphyritic with aphanitic groundmass, vesicular. WR/+10F: pale green to amber-colored minor olivine phenocrysts, locally altered to iddingsite, white laths of plagioclase; vesicles commonly lined with light brown to white clay.	360–385	6308.1–6283.1
	Basalt, medium gray (N5), slightly porphyritic with aphanitic groundmass, vesicular, basalt fragments show some degree of roundness. +35F: contains 10–20% tuffaceous siltstone clasts possibly indicating volcanoclastic sedimentary interlayer occurring within this interval. WR sample is very clay-rich.	385–390	6283.1–6278.1
	Basalt, medium gray (N5), porphyritic with aphanitic groundmass, vesicular. WR/+10F: pale green olivine phenocrysts (10% volume), mostly euhedral (up to 3 mm), commonly altered to reddish iddingsite. Groundmass locally altered; local clay lining vesicles.	390–405	6278.1–6263.1
	Basalt, medium gray (N5), weakly porphyritic with aphanitic groundmass, highly vesicular to massive. WR/+10F: pale green euhedral (up to 3 mm) olivine phenocrysts. Amygdaloidal clay, locally limonitic, very common.	405–430	6263.1–6238.1
	Basalt, light gray (N6), slightly porphyritic with aphanitic groundmass, massive. WR/+10F: olivine phenocrysts mostly replaced by iddingsite. Groundmass is partially altered.	430–445	6238.1–6223.1
	Basalt, light gray (N7), porphyritic with aphanitic groundmass, massive to partly scoriaceous. WR/+10F: coarse (up to 5 mm) olivine phenocrysts entirely replaced by iddingsite. Interval is distinctive for its strong alteration of groundmass feldspars, resulting in a pitted surface texture and generally bleached coloration. The interval 460–465 ft contains 40–50% reddish-brown iron-oxide-stained scoriaceous basalt fragments.	445–465	6223.1–6203.1

Geologic Unit	Lithologic Description	Sample Interval (ft bgs)	Elevation Range (ft above msl)
Tb, Cerros del Rio Basalt	Basalt/scoria, dusky red (5YR 3/4), slightly porphyritic with aphanitic groundmass, scoriaceous. WR/+10F: olivine phenocrysts entirely replaced by iddingsite, intense iron-oxide staining throughout, amygdaloidal clay common. The interval 480–485 ft has 40–50% massive, less vesicular basalt mixed with scoria. Basal contact of scoriaceous basalt estimated at 483 ft bgs.	465–485	6203.1–6183.1
	Basalt, light gray (N6), porphyritic with aphanitic groundmass, vesicular to massive. WR/+10F: olivine phenocrysts entirely replaced by dark red iddingsite. Groundmass has local iron-oxide staining, moderately altered.	485–495	6183.1–6173.1
	Basalt, very light gray (N7), porphyritic with aphanitic groundmass, massive. WR/10F: olivine phenocrysts rimmed or totally replaced by iddingsite; groundmass almost completely altered. Selected fragments are distinctly rounded, possibly the result of abrasion from the drilling process.	495–510	6173.1–6158.1
	Basalt, light gray (N6), porphyritic with aphanitic groundmass, massive. WR/+10F: olivine phenocrysts rimmed or entirely replaced by dark red iddingsite; groundmass almost completely altered and bleached. Selected fragments are well rounded, suggesting they were milled during drilling.	510–540	6158.1–6128.1
	Basalt, light gray (N6), porphyritic with aphanitic groundmass, massive. WR/+10F: olivine phenocrysts replaced by iddingsite. Groundmass altered.	540–545	6128.1–6123.1
	Basalt, medium gray (N5), porphyritic with aphanitic groundmass, massive. WR/+10F: olivine phenocrysts locally replaced (iddingsite), traces of clay and Mn-oxide.	545–555	6123.1–6113.1
	Basalt, medium gray (N5), porphyritic with aphanitic groundmass, massive. WR/+10F: olivine phenocrysts locally rimmed or replaced by iddingsite, minor clay present.	555–565	6113.1–6101.1
	Basalt, medium gray (N5), porphyritic with aphanitic groundmass, massive. WR/+10F: olivine phenocrysts rimmed or replaced by iddingsite, local clay present in lower 10 ft of interval.	565–585	6101.1–6081.1
	Basalt, light olive gray (5Y 6/1), porphyritic with aphanitic groundmass, massive. WR/+10F: olivine phenocrysts unaltered to rimmed or replaced by iddingsite, minor plagioclase phenocrysts.	585–595	6081.1–6071.1
	Basalt, medium gray (N6), porphyritic with aphanitic groundmass, massive. WR/+10F: olivine phenocrysts mostly altered to iddingsite; locally rounded clasts.	595–600	6071.1–6066.1
	Basalt, light olive-gray (5Y 6/1), porphyritic with aphanitic groundmass, massive. WR/+10F: olivine phenocrysts show advanced alteration to iddingsite. Numerous rounded basalt clasts with clay coatings suggest possible sedimentary interflow deposit.	600–605	6066.1–6061.1
	Basalt, light olive-gray (5Y 6/1), porphyritic with aphanitic groundmass, massive. WR/+10F: olivine phenocrysts fresh to locally rimmed or replaced by iddingsite, rare plagioclase phenocrysts; clay lining fractures in interval 615–620 ft.	605–625	6061.1–6041.1

Geologic Unit	Lithologic Description	Sample Interval (ft bgs)	Elevation Range (ft above msl)
Tb, Cerros del Rio Basalt	Basalt, light olive-gray (5Y 6/1), porphyritic with aphanitic groundmass, massive to partly vesicular. WR/+10F: olivine phenocrysts show varying states of iddingsite alteration; clay amygdules present. Some clasts partly rounded.	625–635	6041.1–6031.1
	Basalt, light olive-gray (5Y 6/1), porphyritic with aphanitic groundmass, massive. WR/+10F: olivine phenocrysts fresh to locally rimmed or replaced by iddingsite, rare pyroxene phenocrysts.	635–650	6031.1–6016.1
	Basalt, light olive-gray (5Y 6/1), porphyritic, groundmass aphanitic to microcrystalline, massive. WR/+10F: phenocrysts of olivine, pyroxene, plagioclase, olivines unaltered to slightly altered (iddingsite), pyroxenes prismatic crystals giving rock a speckled appearance; groundmass microcrystalline with laths of plagioclase visible.	650–685	6016.1–5981.1
	Basalt, light olive-gray (5Y 6/1), porphyritic, groundmass microcrystalline, massive. WR/+10F: phenocrysts of olivine (up to 2 mm) and plagioclase, olivines unaltered to locally rimmed or replaced by iddingsite.	685–705	5981.1–5961.1
	Basalt, light olive-gray (5Y 6/1), porphyritic with aphanitic groundmass, massive. WR/+10F: phenocrysts of olivine, pyroxene, and plagioclase; olivines fresh to locally altered (iddingsite), prismatic pyroxenes impart a speckled texture to rock; clasts locally rounded.	705–710	5961.1–5956.1
	Basalt, dark olive-gray to black (5Y 2/1), porphyritic with aphanitic groundmass, vesicular. WR/+10F: olivine phenocrysts of varying stages of iddingsite replacement; rock locally has cinder or glassy appearance; cinders commonly coated with clay, calcite, or zeolite.	710–715	5956.1–5951.1
	Basalt, medium gray (N5), porphyritic with aphanitic groundmass, vesicular. WR/+10F: phenocrysts of olivine, plagioclase, and pyroxene; olivines partly altered or replaced (iddingsite).	715–725	5951.1–5941.1
	Basalt, medium to dark gray (N4), porphyritic with aphanitic groundmass, vesicular. WR/+10F: phenocrysts of olivine and plagioclase, olivines partly replaced or rimmed by iddingsite, fragments have cinder appearance, cinders coated with clay, calcite, or zeolite.	725–730	5941.1–5936.1
	Volcaniclastic sediments, clayey gravel (GC), pale yellowish-brown (10YR 6/2), pebbles (up to 3.0 cm) mostly angular. WR/+10F: 100% lithic clasts made up of dacite, basalt, and pink siltstone.	730–735	5936.1–5931.1
Tpf, Puye Formation	Volcaniclastic sediments, gravel (GW) with silt and sand, grayish-orange pink (5YR 7/2), pebbles (up to 2.7 cm) are angular to subangular. WR/+10F: 98% lithic clasts made up of dacite and vesicular basalt, 2% pale orange quartz.	735–740	5931.1–5926.1
	Volcaniclastic sediments, clayey gravel (GC), medium orange pink (10R 7/4), clasts angular to subrounded. WR/+10F: 90% lithic clasts made up of laminated siltstone and sandstone, 10% basalt with iddingsite alteration and intermediate volcanics (dacite). Interval may represent a clay interlayer.	740–745	5926.1–5921.1
	Volcaniclastic sediments, gravel (GW) with sand and clay, light olive-gray (5Y 6/1), sand and pebbles (up to 5.0 mm), clasts subangular to subrounded. WR/+10F: lithic clasts made up of 70% basalt, 20% dacite, and 10% sandstone/siltstone.	745–750	5921.1–5916.1

Geologic Unit	Lithologic Description	Sample Interval (ft bgs)	Elevation Range (ft above msl)
Tpf, Puye Formation	Volcaniclastic sediments, gravelly sand (SW), light gray (N6), clasts (up to 1 cm) angular to subrounded. WR/+10F: lithic clasts composed of 40–50% glassy basaltic scoria, 50–60% porphyritic dacite. Note: glassy basaltic scoria common in the interval 750–787 ft.	750–757	5916.1–5909.1
	Volcaniclastic sediments, gravel (GW) with silt and sand, light olive-gray (5Y 6/1), pebble gravel with silty matrix, clasts (up to 5.0 mm) angular to subrounded. WR/+10F: lithic clasts composed of 70–80% porphyritic dacite, 20–30% glassy basaltic scoria.	757–762	5909.1–5904.1
	Volcaniclastic sediments, gravel (GP), light gray (N6) to varicolored, pebbles (up to 1.5 cm) are subangular to subrounded. WR/+10F: lithic clasts composed of 80% silicified porphyritic dacite, 20% basaltic scoria.	762–767	5940.1–5935.1
	Volcaniclastic sediments, gravel (GW) with sand and silt, grayish-orange (10YR 7/4), pebbles (up to 1.7 cm) in matrix of sandy silt, clasts subangular to subrounded. WR/+10F: lithic clasts composed of 30–50% silicified dacite, 10–30% tuffaceous siltstone, and 10–20% basaltic scoria.	767–777	5935.1–5925.1
	Volcaniclastic sediments, gravel (GW) with sand, light gray (N6) to varicolored, clasts (up to 1.0 cm) subangular to subrounded. WR/+10F: lithic clasts composed of 70–80% dacite and andesite, 10–20% basaltic scoria, and 10–15% tuffaceous siltstone.	777–787	5925.1–5915.1
	Volcaniclastic sediments, gravel (GW) with sand and clay, light olive gray (5Y 6/1), clasts (up to 3.0 cm) subrounded to rounded. WR/+10F: lithic clasts composed of 70–80% dacite, 5–10% basalt, and 5% tuffaceous siltstone.	787–792	5915.1–5910.1
	Volcaniclastic sediments, sand (SW) with gravel and clay, light brownish-gray (5YR 6/1), pebbles (up to 1.2 cm) are subangular to subrounded. WR/+10F: lithic clasts composed of 90–95% dacite, 5% tuffaceous siltstone, and minor basaltic scoria.	792–812	5910.1–5890.1
	Volcaniclastic sediments, sand (SW) with gravel, light brownish-gray (5YR 6/1), medium to very coarse sand, pebbles (up to 1.0 cm) are subangular to subrounded. WR/+10F: lithic clasts composed of 85–95% dacite and andesite, 5–7% dacitic pumice fragments, and minor basaltic scoria.	812–827	5890.1–5885.1
	Volcaniclastic sediments, sand (SW) with gravel and silt, grayish-orange pink (5YR 7/2), clasts (up to 1.3 cm) subangular to rounded. WR/+10F: lithic clasts composed of 95–98% dacite and lesser andesite.	827–832	5885.1–5880.1
	Volcaniclastic sediments, gravel (GW) with sand, light gray (N6) to varicolored, clasts (up to 2.0 cm) subangular to rounded. WR/+10F: lithic clasts composed of dacite, andesite, basalt scoria, and tuffaceous siltstone.	832–837	5880.1–5875.1
	Volcaniclastic sediments, gravel (GW) with sand, light brownish-gray (5YR 6/1), clasts (up to 3.0 cm) subangular to subrounded. WR/+10F: composed of 99% dacite to rhyodacite clasts. Note: coarse gravel interval.	837–847	5875.1–5865.1

Geologic Unit	Lithologic Description	Sample Interval (ft bgs)	Elevation Range (ft above msl)
Tpf, Puye Formation	Volcaniclastic sediments, gravel (GW) with sand, light brownish-gray (5YR 6/1), clasts (up to 1.3 cm) subrounded to rounded. WR/+10F: clasts composed of 98% dacite, rhyodacite, and minor basalt.	847–854	5865.1–5858.1
	Volcaniclastic sediments, clayey sand (SC) with gravel, grayish-pink (%YR 7/2), clasts (up to 5 mm) are subangular to rounded. +10F: clasts composed of 90–95% dacite and rhyodacite, 5–10% vesicular basalt. WR samples have clayey matrix.	854–868	5858.1–5844.1
	Volcaniclastic sediments, gravel (GW) with clay and sand, grayish-pink (5YR 7/2), clasts (up to 2.2 cm) are subangular to rounded. WR/+10F: clasts composed of 95–98% dacite and rhyodacite; 3–5% tuffaceous sandstone, trace quartzite	868–888	5844.1–5824.1
	Volcaniclastic sediments, sand (SW) with gravel, light brownish-gray (5YR 6/1), medium to very coarse sand with pebbles (up to 1.7 cm), subangular to subrounded. WR/+10F: clasts composed of 99% dacite and rhyodacite.	888–908	5824.1–5804.1
	Volcaniclastic sediments, clayey gravel (GC) with sand, grayish-pink (5YR 7/2), clasts (up to 1.0 cm) are subangular to subrounded. +10F: clasts composed of 95–98% dacite and rhyodacite; 3–5% tuffaceous sandstone. +35F: contains 50–60% brown tuffaceous siltstone/sandstone. WR sample is clay rich.	908–918	5804.1–5794.1
	Volcaniclastic sediments, sand (SW) with gravel and silt, grayish-pink (5YR 7/2), clasts (up to 1.2 cm) are subangular to subrounded. WR/+10F: clasts composed of 98% dacite and rhyodacite, minor volcanic siltstone to fine-grained sandstone, minor pumice.	918–933	5794.1–5779.1
	Volcaniclastic sediments, silty sand (SM) with gravel, light pinkish-gray (5YR 7/2), clasts (up to 1.8 cm), subangular to subrounded. WR/+10F: clasts composed of 95–98% porphyritic dacite, 3–5% fine-grained tuffaceous sandstone. +35F: limonite-cemented grains, crystals very common.	933–938	5779.1–5774.1
	Volcaniclastic sediments, gravel (GW) with sand, light gray (N6) to pinkish-gray, clasts (up to 1.5 cm) are subangular to rounded. WR/+10F: clasts composed of 99% dacite and rhyodacite.	938–943	5774.1–5769.1
	Volcaniclastic sediments, gravelly sand (SW) with silt, light pinkish-gray (5YR 7/2), clasts (up to 1.0 cm) are subangular to rounded; many clasts broken, suggesting coarse gravel. WR/+10F: clasts composed of 99% dacite and rhyodacite, trace pumice.	943–963	5769.1–5749.1
	Volcaniclastic sediments, gravel (GW) with sand, light brownish-gray (5YR 6/1), clasts (up to 1.5 cm) are subrounded to subangular. WR/+10F: clasts composed of 100% dacite, rhyodacite, and andesite, trace pumice. +35F: contains 90% volcanic lithics, 10% free quartz and sanidine crystals. Upper 5 ft of the interval has clayey matrix.	963–973	5749.1–5739.1
	Volcaniclastic sediments, sand (SP), light brownish-gray (5YR 6/1), medium to very coarse sand and granules (up to 0.5 mm), subangular to rounded. WR/+10F: composed of porphyritic dacite, rhyodacite, and andesite. +35F: contains 5% free quartz and sanidine crystals.	973–983	5739.1–5729.1

Geologic Unit	Lithologic Description	Sample Interval (ft bgs)	Elevation Range (ft above msl)
Tpf, Puye Formation	Volcaniclastic sediments, sand (SW), yellowish-brown (10YR 5/4), very fine to very coarse sand and granules (up to 0.3 mm), subrounded to subangular. +10F: composed of porphyritic dacite and rhyodacite (less than 10% of the entire sample retained by the No. 10 sieve). Note: fine clastic interval.	983–998	5729.1–5714.1
	Volcaniclastic sediments, sand (SW) with gravel, light brown (5YR 6/4), subrounded to rounded grains (up to 1.0 cm). +10F: 98% white aphyric pumice, minor basalt scoria and dacite. +30F: 80–90% volcanic lithics, 10% quartz and sanidine crystals. Note: pumice-rich interval 998–1068 ft.	998–1003	5714.1–5709.1
	Volcaniclastic sediments, gravel (GW) with sand, light gray (N6), to varicolored, clasts (up to 1.2 cm), subrounded to rounded. WR/+10F: 90% silicified dacite porphyry, 10% pumice.	1003–1008	5709.1–5704.1
	Volcaniclastic sediments, gravel (GW) with sand, light gray (N6), clasts subangular to subrounded. WR/+10F: 40–60% aphyric pumice, 40–60% dacitic volcanic lithics, 5–10% tuffaceous sandstone.	1008–1018	5704.1–5694.1
	Volcaniclastic sediments, sand (SP) with gravel, varicolored, white (N9), to light gray (N6), medium to coarse sand with pebbles (up to 1.0 cm) subrounded to rounded. WR/+10F: 50–75% aphyric pumice, 25–30% dacite, rhyodacite, and andesite; 2–5% siltstone.	1018–1033	5694.1–5679.1
	Volcaniclastic sediments, sand (SW) with gravel, varicolored, white (N9) to dark gray (N6), clasts (up to 1.0 cm) subrounded to rounded. WR/+10F: 60–80% white and gray pumice, 10–20% dacite and basaltic scoria, and intermediate to felsic volcanics, 5–10% volcanic sandstone.	1033–1043	5679.1–5669.1
	Volcaniclastic sediments, gravel (GW) with sand, varicolored, white (N9) to light gray (N6), clasts (up to 2.0 cm) subangular to subrounded. WR/+10F: 60–80% white and gray pumice, 20–30% dacite and silicified dacite, 10–20% tuffaceous sandstone.	1043–1058	5669.1–5654.1
	Volcaniclastic sediments, gravel (GW) with sand, varicolored, white (N9) to light tan, clasts (up to 1.0 cm) subangular to subrounded. WR/+10F: 75–80% white and gray pumice, 15% silicified dacite, 5% fine-grained volcanic sandstone, 1–2% quartz and sanidine crystals.	1058–1063	5654.1–5639.1
	Volcaniclastic sediments, gravel (GW) with sand, varicolored, white (N9) to light gray (N6), clasts (up to 1.5 cm) subangular to subrounded. WR/+10F: 85% white pumice, 10–15% silicified dacite, 10–15% fine-grained volcanic sandstone. +35F: 10–20% pumice, 70–75% lithics, 3–5% quartz and sanidine crystals, 10–15% volcanic sandstone, minor quartzite.	1063–1068	5639.1–5634.1
	Clastic sediments, sand (SW) with gravel, varicolored, white (N9) to light gray (N6), clasts (up to 5 mm) subangular to subrounded. WR/+10F: 75–80% flow-banded rhyodacite and dacite, 3–5% pumice, 10–15% volcanic sandstone, 3–5% quartzite. Note: first interval with significant Precambrian lithic components indicates river gravel deposits within the Puye Formation from 1068 to 1133 ft bgs.	1068–1073	5634.1–5629.1

Geologic Unit	Lithologic Description	Sample Interval (ft bgs)	Elevation Range (ft above msl)
Tpf, Puye Formation	Clastic sediments, gravel (GW) with sand, varicolored, white (N9) to light gray (N6), clasts (up to 1.5 cm) subrounded to rounded. WR/+10F: 75–85% volcanic lithics (andesite, dacite, rhyodacite), 5–10% fine-grained volcanic sandstone, 5–10% white to pinkish quartzite, trace granitic rocks, 1–2% quartz and sanidine crystals.	1073–1083	5629.1–5619.1
	Clastic sediments, gravel (GW) with sand, light brownish-gray (5YR 6/1), clasts (up to 1.5 cm) subrounded to rounded. WR/+10F: 60–80% rhyodacite and dacite, 20–40% quartzite, 5–10% granitic rocks.	1083–1093	5619.1–5609.1
	Clastic sediments, gravel (GW) with sand, varicolored, white (N9) to light gray (N6), clasts (up to 1.5 cm) subrounded to rounded. WR/+10F: 70–80% volcanic lithics (andesite, dacite, rhyodacite), 10–30% quartzite.	1093–1103	5609.1–5599.1
	Clastic sediments, sand (SW) with gravel, pale yellowish-brownish gray (5YR 6/2), fine to medium sand with pebbles (up to 1.5 cm), subrounded to rounded. WR/+10F: 80–90% porphyritic dacite, 5–10% vesicular basalt, 2–5% quartzite.	1103–1108	5599.1–5594.1
	Clastic sediments, gravelly sand (SW), medium brown (5YR 5/4), fine to medium sand with pebbles (up to 1.0 cm), subrounded to rounded. WR/+10F: 60–80% andesite and dacite, 10–30% vesicular basalt, 5–10% quartzite, minor tuffaceous sandstone.	1108–1118	5594.1–5584.1
	Clastic sediments, sand (SW) with gravel and clay, pale brownish-gray (5YR 7/2), fine to coarse sand with pebbles (up to 1.5 cm), subangular to rounded. WR/+10F: 10–60% basalt, 30–50% rhyodacite and dacite, 5–10% quartzite.	1118–1128	5584.1–5574.1
	Clastic sediments, gravel (GW) with sand, light brownish-gray (5YR 6/1) to varicolored, clasts (up to 2.0 cm), subangular to subrounded. WR/+10F: 70–80% rhyodacite and dacite, 10–20% basalt, 5–10% quartzite, minor granitic rocks, trace micaceous quartzite schist.	1128–1133	5574.1–5559.1
TOTAL DEPTH = 1133 ft bgs			

Notes:

- American Society for Testing Materials (ASTM) standards (D 2488-90: Standard Practice and Identification of Soils [Visual-Manual Procedure]) were used to describe the texture of drill chip samples for sedimentary rocks such as alluvium and the Puye Formation. ASTM method D 2488-90 incorporates the Unified Soil Classification System (USCS) as a standard for field examination and description of soils. The following standard USCS symbols were used in the R-13 lithologic log:
SW = Well-graded sand GM = Silty gravel SC = Sand/clay
GW = Well graded gravel GC = Clayey gravel SP = Sand
GP = Poorly graded gravel SM = Silt
- Cuttings were collected at nominal 5-ft intervals and divided into three sample splits: (1) unsieved, or whole rock (WR) sample; (2) +10F sieved fraction (No. 10 sieve equivalent to 2.0 mm); and (3) +35F sieved fraction (No. 35 sieve equivalent to 0.50 mm).
- The term *percent*, as used in the above descriptions, refers to percent by volume for a given sample component.
- Color designations such as hue, value, and chroma (e.g., 5YR 5/2) are from the Geological Society of America's Rock Color Chart.

Appendix C

Borehole Video
(*CD on inside back cover*)

Appendix D

*Schlumberger Geophysical Report and Montages
(CD on inside back cover)*

